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Overtopping and Overflow of Flood Protection Embankments – Risk Reduction of Embankment Dam Failure by the Use of Geosynthetics

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ABSTRACT: In most cases common levee cross-section designs do not provide any safety against erosion of the slopes if crest overflow occurs. Recent floods highlighted again the vulnerability and risk of levee failure due to uncontrolled crest overflow, which results usually in the development of a breach and, consequently, in flooding of the downstream flood plains. The application of geosynthetics comprises many advantages such as the avoidance of damages, the deceleration of polder flooding and the stability increase of affected slopes. Particularly, the economic aspects are attractive for the investor since the design allows steeper slopes which saves earth works whilst providing overflow protection and avoiding long-term costs caused by flooding. The application of geosynthetics for overflow protection systems structures is still in research phase, although hydraulic and geotechnical institutes worldwide have carried out large scale model tests successfully. Further geosynthetic protection systems belong to the state of the art in coastal engineering where overtopping and surge loads are common design criteria. This fact confirms the general applicability of geosynthetics resisting strong dynamic hydraulic loads.

Keywords: geosynthetics, dams, dikes, crest overflow, overtopping

1 INTRODUCTION

In recent decades several major flood events have shown the vulnerability of flood protection structures. 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 losses. Particularly, long lasting floods and locally concentrated extreme short lasting precipitation events were responsible for countless natural disasters (Heerten & Horlacher, 2002). Locally and regionally, the threats and risks may increase, as forecasted by several hydrological scientists and researchers (Hennegriff et al., 2006).

In Germany, the design of flood protection levees against overtopping and overflow loads is neither state of the art nor applied in practice (Haselsteiner et al., 2007b; DIN 19712, 1997; DWA M507, 2007). Only quite limited overflow sections have been constructed mostly using classical methods such as riprap and/or the application of binding materials (asphalt, cement, lime). For classical methods both long-term experience and design methods are available (LFU BW, 2004; Bosshard, 1991; CIRIA 116/1987; Powledge et al., 1989). Although, several German research institutes have carried out laboratory tests with geosynthetic protected overflow dikes successfully (Bieberstein, 2003; Haselsteiner, 2007a, b, c and others) the next step to develop a design method has not been carried out. LFU BW (2004) has already confirmed the applicability and economic efficiency of geosynthetic methods for overflow protection systems: *"In principle these [geosynthetic] construction methods allow considerable higher loads and steeper downstream slopes, hence, they can be also of importance in terms of economical aspects."*

Fundamental aspects of the application and effects of overflow protection measures using geosynthetics are discussed in Werth et al. (2007) (see also Haselsteiner et al., 2008). Overflow sections along rivers can be an effective means within flood protection concepts, in order to activate polders and to reduce peak discharges in downstream regions. The application of geosynthetics for this purpose combines both low construction costs and an extremely robust and durable structure if the corresponding, already available design principles are considered.

The proof and verification of new construction or design methods can be achieved by the application of accredited analysis or by full scale tests as already carried out by several hydraulic or geotechnical institutes worldwide. In spite of the successful full scale test results, and in spite of the unanimous agreement of researchers and engineers that the described methods can be favourable in comparison to classical methods under certain circumstances, the decision making parties such as authorities, owners and municipalities, etc. still hesitate to switch from the classical to geosynthetic methods. This is also true for the design of spillways of small dams since the corresponding design codes, regulations and recommendations based on theoretical studies and practical testing are missing or are do not belong to the state of the art which is defined in the corresponding codes, regulations, manuals, etc. The authors hold the opinion that the principles for the design of these structures are well-known and understood that only limited research work is required to develop mentioned design method and criteria which enables a standard application. Both the stress-deformation behaviour of corresponding structures and the hydrodynamic loads are still to be investigated in detail. For both of these research fields the fundamentals have been sufficiently developed and the physical basics are well described that the final step is “only” to be reflected by the superposition of the existing knowledge and experience of two basic subjects. Corresponding research works can be performed within the scope of applied science studies.

2 APPLICATION OF GEOSYNTHETICS FOR FLOOD PROTECTION DIKES

The application of geosynthetics in geotechnical and hydraulic engineering is described in Saathoff (2003) including also the field of flood protection dikes and embankment dams (see also Saathoff & Werth, 2003). The refurbishment of dikes has gained more importance in Western Europe since most of the flood protection dikes were built centuries ago. However, the modern techniques and methods of geotechnical and hydraulic engineering have only been applied approx. 50 – 75 years after the fundamentals of these fields were established. The application of geosynthetics for the refurbishment of dikes belongs to the state of the art regarding geosynthetic filters, reinforcement and sealings (Heerten & Werth, 2006; see Fig. 1).

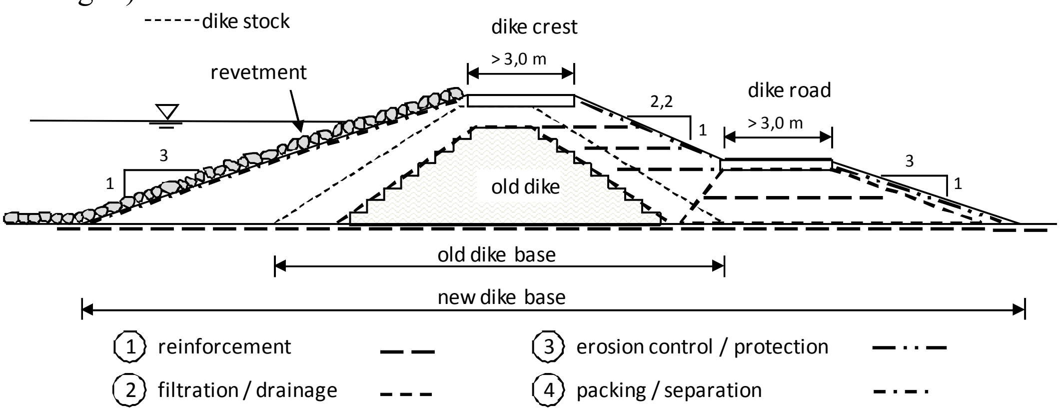

Figure 1. Application of geosynthetics within embankment dam and flood embankment structures (Haselsteiner, 2006)

Geosynthetic clay liners in particular (shown in Fig. 2) have been frequently applied in recent dike refurbishment measures in order to control seepage and to reduce water pressure in the dike body. The geosynthetic clay liner reflects an alternative to a natural clay surface sealing. Mostly, the persistent permeability of the geosynthetic clay liners were doubted, but it could be confirmed by long-term investigations and results (EAG-GTD, 2002; Egloffstein, 2001; Heerten et al., 2008). Geosynthetic filters are usually applied with a loading berm at the downstream slope of the dike. Thus, the original dike material shall be filtered in consideration of the usage of coarse, permeable fill material for the berm. Where soft, compressible soil such as turf is located beneath the dike base, geosynthetic grids may reduce settlement and deformation and also enable foundation on usually unsuitable soils. Of course, turf or other organic soils should not be exposed to harmful hydraulic gradients. If erosive, low cohesive soils are applied as sealing materials in small embankments, the application of geosynthetic filters is also favourable in terms of geometrical constraints in comparison to grain filters. Since this kind of soil exhibits negligible resistance to erosion or shows hydromorphic behaviour, both the underlying soil and the dike body itself have to be sealed. A combination of an underground sealing with a geosynthetic clay liner is shown in Fig. 2 as it can be used for correspondingly designed and loaded dikes.

Experience in applying geosynthetic products within geotechnical and hydraulic engineering has been gained over decades. In Germany, modern and accurate design standards and regulations for the application of geosynthetics were prepared in the eighties and nineties of the last century (EBGEO, 2010; DVWK 76, 1988). Since then, more and more experience and information has been gathered through the construction of many projects. Furthermore, the use of geosynthetics was also investigated for overflow protection issues at embankment dams including both coastal and river related structures.

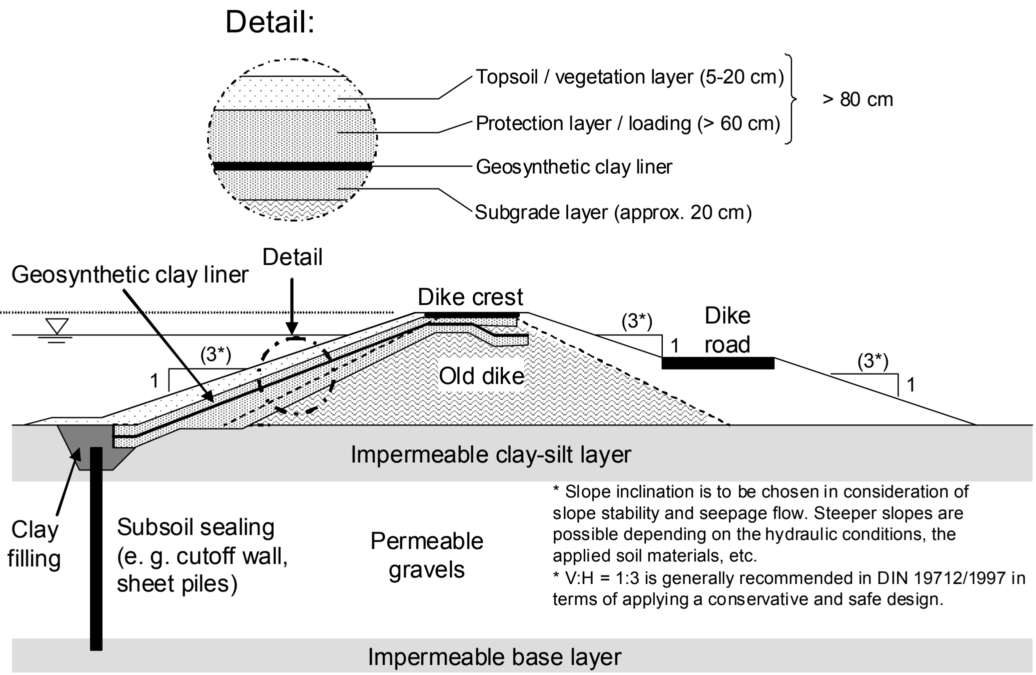

Figure 2. Application of a geosynthetic clay liner in the course of dike refurbishment works (Haselsteiner & Strobl, 2005)

Fig. 3 depicts an levee cross-section optimally reinforced and protected with geosynthetics. This cross-section of the levee was implemented in Poland after the 1997 Oder River flood. It offers optimal prerequisites for a long-term, protective, stable and overflow-secure levee. Its waterside 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 against overflow risks provided by encapsulating levee core material in nonwovens with the wrap-around method. A filter-effective configuration of air-side drainage is combined with a levee defence roadway. Breach behaviour, as would be exhibited by a levee with conventional cross-section consisting only of earthen materials, can be presumably eliminated.

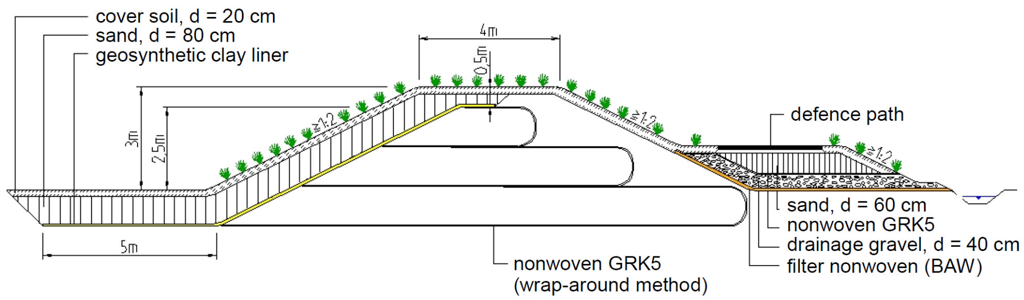

Figure 3. Cross-section of a reconstructed Oder River levee in Poland (Heerten, 1999)

3 BASIC DESIGN PRINCIPLES FOR OVERFLOW DIKES

Overflow protection systems are affected by many parameters and design considerations. For design, the following aspects should at least be taken into consideration and assessed in detail (Haselsteiner et al., 2008):

- Overflow hydraulics (tailwater conditions, specific discharge …)
- Function of overflow protection system (reactivation of retention volume, structural protection, retardation of flooding …)

- Choice of geosynthetic product (geotextile, geogrid, geonets …)
- Function of geosynthetic product (separation, filter, reinforcement …)
- Protection of geosynthetics against environmental impacts (animals, biochemistric fluids, UV radiation …)
- Definition of design overflow discharge and/or height (corresponding to flood protection principles and design criteria …)
- Energy dissipation (stepped spillway, stilling basin …)
- Protection of embankment shoulder, crest and bottom (layers, tubes, containers …)
- Definition of main design parameters (number of layers, layer distance, embedment length, embedment depth, number and length of earth anchors …)
- Soil material specifications (grain size, grain size distribution, shear parameters, permeability …) and subsoil treatment
- Seepage conditions and effects (loads, erosion, suffusion ...)
- Inspection, maintenance, rehabilitation/refurbishment, supervision

The legal framework for the application of geosynthetics in geotechnical and hydraulic engineering is well developed and sophisticated. In particular the quality management and the control of the suppliers are stressed within existing standards, engineering codes, guidelines and manuals. In Germany, the "Forschungsgesellschaft fur Straßen- und Verkehrswesen" which carries out research for roads and traffic engineering is the spearhead for the establishment of standards, specifications and requirements (FSGV, 2005a,b) along with the DIN institute (DIN: Deutsches Institut für Normung) and a few national engineering associations such as the DGGT (Deutsche Gesellschaft for Geotechnik), DVWK (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall). Both in DVWK 221 (1992) and in DGGT EBGEO (1997) the general application fields are summarized and design recommendations and methods are presented (see also Saathoff, 2003). In FSGV (2005 a, b) the appropriate legal framework for the production, delivery, application, control and supervision is given. Geosynthetics are also affected by the work on Eurocode 7 (EC7) due to the European harmonization of the norms and standards and the transition of the German to European standards. Several papers describe the work progress and the effects on the application of geosynthetics (Ziegler, 2007). For reinforcement with geogrids DGGT EBGEO (1997) is helpful but is currently under revision (Bräu, 2007). The publication of the revised version was expected for mid 2010 and has already been published in an updated version in 2009. First experiences are already available and are discussed among researchers and industry (Herold, 2009; Vollmert & Schwerdt, 2010).

Depending on the different design options and situations, most of the research and development work resulted in the conclusion that geosynthetics for overflow protection systems (Fig. 4) can combine both robust design and economical efficiency. For design work, a separation of the specific dike parts is helpful. Thus, the crest, shoulder, slope and the downstream toe require special design considerations and structural solutions. The basic geotechnical and hydraulic aspects were investigated and summarized decades ago by e. g. Bosshard (1991) and Powledge et al. (1989). Also in Germany researchers studied the use of geosynthetics for overflow protection systems 30 years ago (Stalmann, 1980). Recently, overflow protection systems for flood protection dikes including geosynthetic methods were studied at several geotechnical or hydraulic institutes of the universities of Karlsruhe, Stuttgart, Darmstadt and Munich. Most of the research studies were focused on alternative concepts for overflow protection methods without the use of geosynthetics as the main component, except for the tests in Munich at the laboratory of the Institute of Hydraulic and Water Resources Engineering of the Technische Universität München.

This series of tests was carried out in the years 2006/07 at the hydraulic laboratory of the TU Muenchen in Obernach. The tests were focused on construction methods A and B as shown in Fig. 4. Both of the investigated methods revealed a highly robust and durable behaviour when subjected to hydraulic overtopping loads. The maximum load was 300 l/s*m resulting in an overtopping height of approx. 0.35 m. Within the test series downstream dike slopes of V:H = 1:1.5 to 1:2.5 were investigated. Pictures of tested designs A and B are shown in Fig. 5 for both the loaded and unloaded conditions.

In Fig. 6 and Fig. 7 the sections of the two mentioned test dikes are shown. The dike body was built of sand so that also a geosynthetic filter was applied between the gravel, which was used to form the superficial layer beneath the protection cover, and the sand body. A composite made of a geogrid and a nonwoven was installed for the test model as shown in Fig. 6. A needle-punched nonwoven geotextile was used for the model test with a wrap-around method as shown in Fig. 7. Both materials have different stress-strain-behaviour but due to the different application (wrap-around and slope parallel) both systems show high resistance against hydraulic loads.

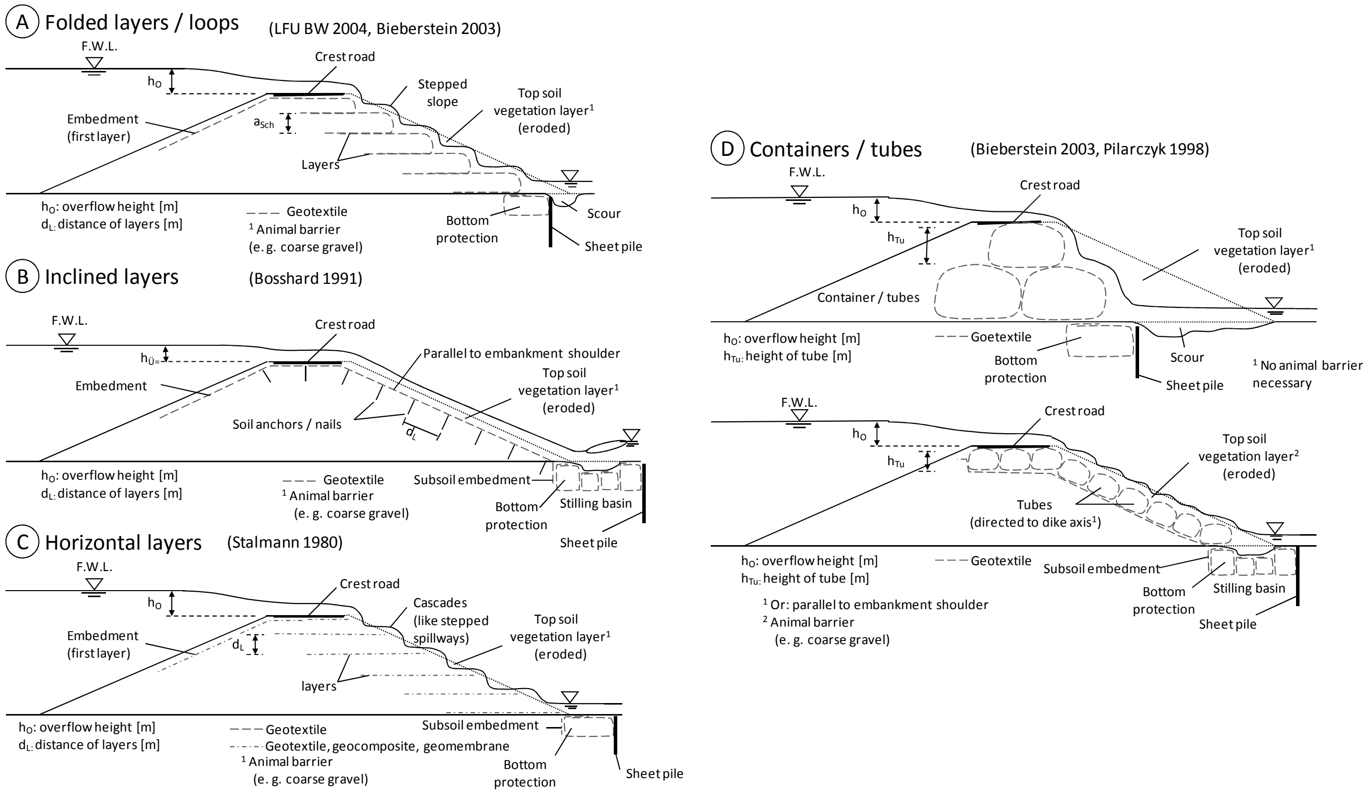

Figure 4. Typical overflow protection systems of flood embankments using geosynthetics (Haselsteiner et al., 2007a)

Figure 5. Loaded and unloaded dyke models with slope parallel geosynthetic layers using anchors for fixation (left) and wrap-around method (loops) (right) (Haselsteiner et al., 2008)

As mentioned in the list of design considerations above, the protection of the crest and toe area was guaranteed by the application of a tube at the toe and by bracing the applied geosynthetics. Both methods survived the tests without remarkable damage or deformation. For the fixed parallel geosynthetics method minor deformations occurred only after the applied soil nails/anchors were subsequently reduced.

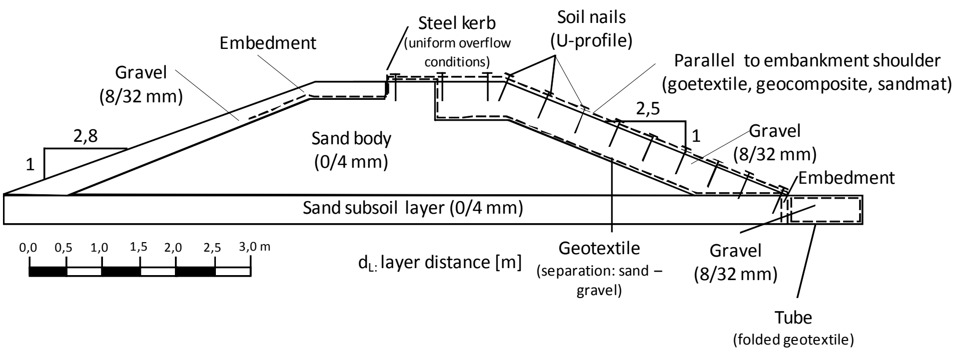

Figure 6. Dike model with layers parallel to embankment shoulder fixed by soil nails (Haselsteiner et al., 2008)

The advantages of the geosynthetic loops are the high robustness and the favourable energy dissipation provided by a stepped spillway. The fixed parallel geosynthetic layers can easily be applied to existing, stripped slopes without interference of the construction process. This method can also have some advantages if only isolated damaged spots are to be refurbished. Within the Munich tests a combination of a vegetation layer and a knitted geotextile was also investigated. For this purpose the downstream slope of the test levee was covered with a topsoil where the knitted geotextiles were placed with different overburden heights of 5-10 cm. The final test series was dominated by a relatively fast failure of the protection system. But, the initiation of the failure began at the area which had not been reinforced by a knitted geotextile. The authors hold the opinion that the application of a knitted geotextile in combination with a topsoil/vegetation layer increases the resistance against erosion considerably. Currently, another test program is in preparation with the close collaboration of industry, engineering consultants and science.

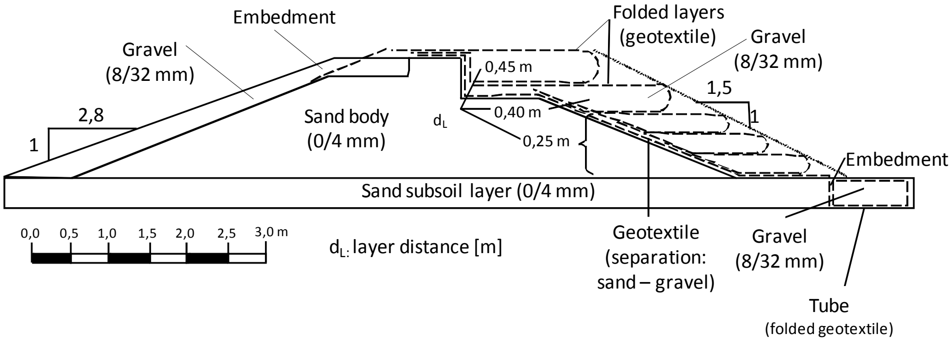

Figure 7. Dike model with wrap-around method (loops) (Haselsteiner et al., 2008)

4 NEEDS FOR RESEARCH

The geotechnical and (geo)hydraulic basics for flood protection embankments/levee overflow/overtopping are well-known as mentioned before. Depending on the preferred methods, (see Fig. 4) corresponding large or full scale laboratory or field tests should be applied in order to determine the hydrodynamic forces resulting from overtopping and the reaction of the geosynthetic protection system. For the described methods A and B (Fig. 4, Fig. 5, Fig. 6, Fig. 7) as well as for method D the stress-deformation behaviour of the applied geotextiles, geogrids and/or geocomposites dominate the embankment stability whereas method C exhibited unstable conditions due to the possibility of backward erosion caused by high hydraulic forces. Once, the stress-deformation behaviour of some of the mentioned design methods are determined, the application limits and required safety factors can be derived by analytical analysis and extrapolation. Future research work should still focus on small embankments where relatively limited deformations and hydrodynamic loads are to be expected. Also, particular attention has to be paid to the design of the crest, re-anchoring area and the downstream dam toe where high hydraulic forces can occur. A failure of the crest and/or the dam toe will inescapably lead to a total failure and, therefore, these parts should be designed conservatively. In terms of the necessity of energy dissipation and the avoidance of scouring downstream, the application of tubes is recommended since those design methods were tested successfully in Munich before.

Method A is a “State of the Art” application for reinforcement of embankments. For the application as overflow protection system, hydrodynamic loads on the stepped spillway and the stress-deformation behaviour of the geosynthetic loops need to be investigated in detail. For this measurement small piezometers and strain gauges can be used. The pore water pressures should be measured at the surface of the steps and in the dike body itself. Seepage uplift forces should be eliminated by using a high permeable fill material within the loops and by the application of an appropriate sealing system. Simultaneously, in order to obtain a better determination of the overflow velocities, an overflow kerb should be applied. Upstream and downstream water levels are important boundary condition parameters to monitor. For the loops, heavy geotextiles are as applicable as geocomposites consisting of a geogrid combined with a geotextile. The decisive research design parameters and aspects shall result in a recommendation of a standard design and they are as follows:

- Determination of specifications of the applied geosynthetic product (strength, permeability…)
- Determination of applicable layer distances and embedment lengths using the wrap-around method
- Determination and evaluation of the design of the steps in terms of energy dissipation and in terms of occurring loads
- Determination of the re-anchoring length / technique

To be competitive with classical overflow protection systems, hydraulic loads of more than 0.5 $m^3/s*m$ (500 litres/s*m) or even higher have to be envisaged. In this context, it has to be repeated that this solution is also a measure to stabilize the slope of the embankment so that the geostatic stability is also considerably increased depending on the applied materials and the actual slope inclination. Therefore, considerably steep slopes (V:H = 1:1.0-1.5) can most probably be applied. In Germany, similar investigations have already been carried out. But, the tests were made applying only limited monitoring and a small scale test dike so that a final design recommendation could not be prepared from the results (Bieberstein, 2003). The height of a test levee should be limited to 2-3 m also considering that most of the existing embankments along rivers have a considerably limited height. For example, the average height of over 1,000 km dikes in Bavaria (Germany) is approx. 2.5 m (Haselsteiner & Strobl, 2005).

Method B is a combination of a geosynthetic cover and soil nails for stabilization. The soil nails perform as anchors and the geosynthetic cover limits the deformation of the dam body and avoids erosion phenomena. Similar to Method A, a coarse grained soil material should be applied or already present within the old dike body. Otherwise a harmful migration / transport of the fines cannot be prevented and this can quickly lead to a total failure. Again, pore water pressures and deformations should be measured. Additionally to the previously mentioned instruments and measurements for Method A the forces on the soil nails should be measured since the arrangement of nails and the form and length of the nails are important aspects. In order to find a suitable standard design the following design parameters and aspects should be taken into consideration:

- Determination of specifications of the applied geosynthetic product (strength, permeability…)
- Determination of applicable soil nail arrangement and soil nail specifications (thickness, length, form, spacing …)
- Determination and evaluation of the energy dissipation and occurring hydrodynamic loads
- Determination of the re-anchoring length / technique

For Method B the applicable slopes are dominated by the natural slope stability of the embankment. Hydrodynamic forces and interflow (seepage) forces increase the loads on the downstream slope of method B (Fig. 4). Therefore, slopes with an inclination flatter than V:H = 1:2.0-2.5 should be used for the tests.

The previously mentioned method(s) D (Fig. 4) have been successfully applied in coastal engineering. For the use of geotextile containers/tubes, particularly for big-packs, the applicable size will be limited by the strength of the applied geosynthetic product. The application for small (H < 2 m) overflow flood protection dikes is also quite attractive and is worth to be discussed in the future.

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