OVERFLOW PROTECTION SYSTEMS OF FLOOD EMBANKMENTS WITH GEOSYNTHETICS

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Abstract: Deceleration of the flooding of polders with large damage potential and/or the prevention of a dike breach in cases of overflow may contribute to reduction of damage and risk. This will be illustrated by comparison of the flooding of a polder by a dike breach and by the overflow of an adequately designed embankment. This simple example shall demonstrate that in either case damages are reduced or avoided.

As an alternative to conventional construction designs for crest overflow, an enhanced geosynthetic application of soil reinforcement is taken into account based on results of geosynthetic-reinforced dike model tests including hydrodynamic loads caused by crest overflow. Results from the model tests show that it can be assumed that the safety of dikes against total failure due to crest overflow can be increased significantly, but further design criteria assessments, including hydrodynamic effects on geosynthetic reinforcement layers, are required.

In the paper, different construction methods for the design of overflow dikes are presented. Some of the presented constructions were tested within a research project at Institute of Hydraulic and Water Resources Engineering of the Technische Universitaet Muenchen. The results of these tests are briefly summarised. Moreover, some basic construction design criteria such as active embedment length of the reinforcement layers and required layer distance are discussed and illustrated by a practical design example. Assumptions on hydraulic loads are as important as the calculation of slope stability of reinforced soils and an assessment of internal erosion processes. Possible economical benefits as part of construction depend on site specific conditions and particularly on the height of the dike, the existing slopes and the foreseen hydraulic loads.

Keywords: earth dam, geosynthetic, reinforced embankment, geotextile, geogrid, embankment

INTRODUCTION

Normal flood embankments along rivers are not designed for overflow loads, except special designed overflow sections. Overflow areas are very rare, nevertheless the reactivation of flood retention volume is one of the main aims of the German national water management law. The technical code for flood protection dikes along rivers (DIN 19712 1997) excludes that the protection of the landside embankment from technical standard structures because of high costs and poor experience with such structures. Thus, overflow loads mostly lead to a very rapid and complete failure of the dike body forming a dike breach with lengths from a few meters to several hundreds of meters. A huge part of the damages that occurred due to dike breaches during the flood incidents 1999, 2002 and 2005 in Germany could have been avoided by focusing the application of overflow protection structures. Hereby the fact should be kept in mind that overtopping or overflow is the most likely reason for dike failure. Additionally, flood protection measures in order to avoid overtopping bear a high risk for the flood task forces.

One major issue objecting to overflow dike structures are the high costs. This aspect can be met by using designs incorporating geosynthetics. Model tests showed that special protected dikes using geosynthetics can withstand overflow heights up to 0,30 m and more (Haselsteiner et al. 2007a). These measures lead to a retardation of the flooding of the hinterland located behind the dike and additionally a complete failure is avoided. Both effects result in a reduction of flood damages and in gaining more time for taking other flood protection measures. Although a lot examination work on the field of this topic had been carried out centuries ago (Powledge et al. 1989, CIRIA 116 1987, Stalmann 1981) no design specification or standards were created. Nevertheless, in comparison to commonly used overflow protection measures such as riprap or just flat embankment inclinations geosynthetic overflow structures are an effective and efficient solution. Hereby, LFU BW (2004) admits that basically this kind of structures can withstand higher loads and have steeper embankment inclinations than other structures what put emphasis on the efficiency and bearing capacity.

GENERAL APPLICATION OF GEOSYNTHETICS IN EMBANKMENT DAMS AND DIKES

Within flood embankments geosynthetics are used for sealing, draining, filtering, for erosion protection and soil reinforcement. Typical applications of geosynthetics are presented in Figure 1 and are listed below.

- Sealing of dikes by using geosynthetic clay liners
- Geotextiles as filter
- Geogrids as soil reinforcement
- Subsoil improvement underneath dike roads
- Application as container and tubes within coastal engineering
- …

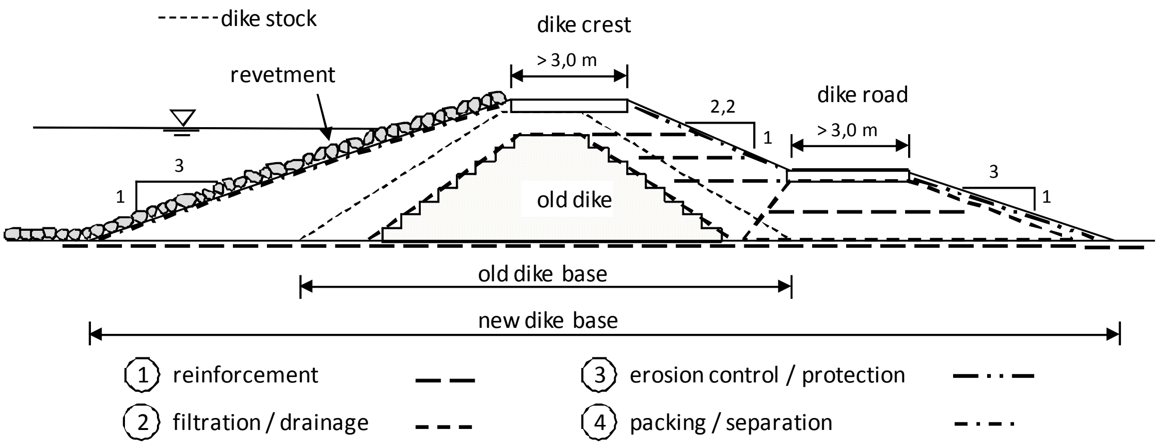

Figure 1. Application of geosynthetics within embankment dam and dike structures (Haselsteiner 2006, Saathoff & Zitscher 2001)

After recent flood incidents during the last century at the rivers Elbe, Oder and Danube in Germany many dikes were refurbished by applying geosynthetic clay liners as sealing elements. Moreover, geogrids were installed particularly underneath dike roads to improve stability and to reduce settlement within weak subsoil. Compared to granular filters, geosynthetic filters are often preferred because of their efficiencies and their simple use. In addition, granular filters have usually a thickness of minimum 0,50 m that mostly cannot be integrated in a sound and economical layout, especially within small flood embankments (Saathoff & Werth 2003).

OVERFLOW PROTECTION MEASURES USING GEOSYNTHETICS

In Germany and worldwide the application of geosynthetic overflow protection systems focuses on coastal areas (Restall et al. 2004). In coastal engineering particularly container and tubes are used for the protection of bays, harbours and shorelines against wave impact. Within flood protection embankments the use of geosynthetics are limited to applications that are described in Figure 1, despite of research work proved the benefit for overflow protection (Haselsteiner et al. 2007a, Werth et al. 2007, Bieberstein 2003).

Layout of overflow protection systems using geosynthetics

Typical sections for overflow dike sections are shown in Figure 2. The protection zone reaches from the waterside dike shoulder to the bottom of the landside dike toe implicating special measures for energy dissipation and scour avoidance. Geosynthetic layers can be installed in horizontal layers (Figure 2. A, C) or tubes/containers (Figure 2. D) or parallel to slope inclination (Figure 2. B). A special way of protection is the use of mega tubes as dike core, as it is done within coastal engineering. Systems with inclined layers usually have to be fixed by earth anchors or nails to provide compound and to reduce deformation. Toe protection can be guaranteed by all sorts of piles or embedded tubes or containers. The depth of toe protection structures should be chosen sufficiently due to avoid scouring.

Overflow protection systems are affected by many parameters and design considerations. Concerning the design, some aspects should be taken into account and be assessed:

- Function of overflow protection system (reactivation of retention volume, structural protection, retardation of flooding …)
- Choice of geosynthetic product (geotextile, geogrid …)
- Function of geosynthetic product (separation, filter, reinforcement …)
- Protection of geosynthetics against environmental impacts (animal, biochemistric fluids, UV radiation …)
- Definition of design overflow discharge or height
- Energy dissipation (stepped spillway, stilling basin …)
- Protection of embankment shoulder, crest and bottom (layers, tubes, containers …)
- Specifications due to layout considering dike geometry, soil material, subsoil conditions and loads
- Definition of main design parameters (number of layers, layer distance, embedment length, embedment depth, inclination, number and length of earth anchors …)
- Soil material specifications (grain size, grain size distribution, shear parameters, permeability …)
- Seepage conditions and effects (loads, erosion, suffusion ...)
- Overflow hydraulics (tailwater conditions, specific discharge …)
- …

Specific discharges for similar structures are limited to a maximum of 1.0 $m^3/s/m$, what is leading to overflow heights below 1.0 m. As geosynthetics have poor resistance to animal impact, barriers should be provided. Here, coarse gravel layers are a cheap and effective solution. Both landscape and safety issues would prefer top soil vegetation layers that may be eroded in case of overflow. The geosynthetic top layer or tube has to be fixed. A simple solution is a anchoring at the waterside embankment shoulder. For the limitation of deformation the use of geogrids is advisable, nevertheless model tests approved a sufficiently strong material strength of not reinforced geotextiles, too.

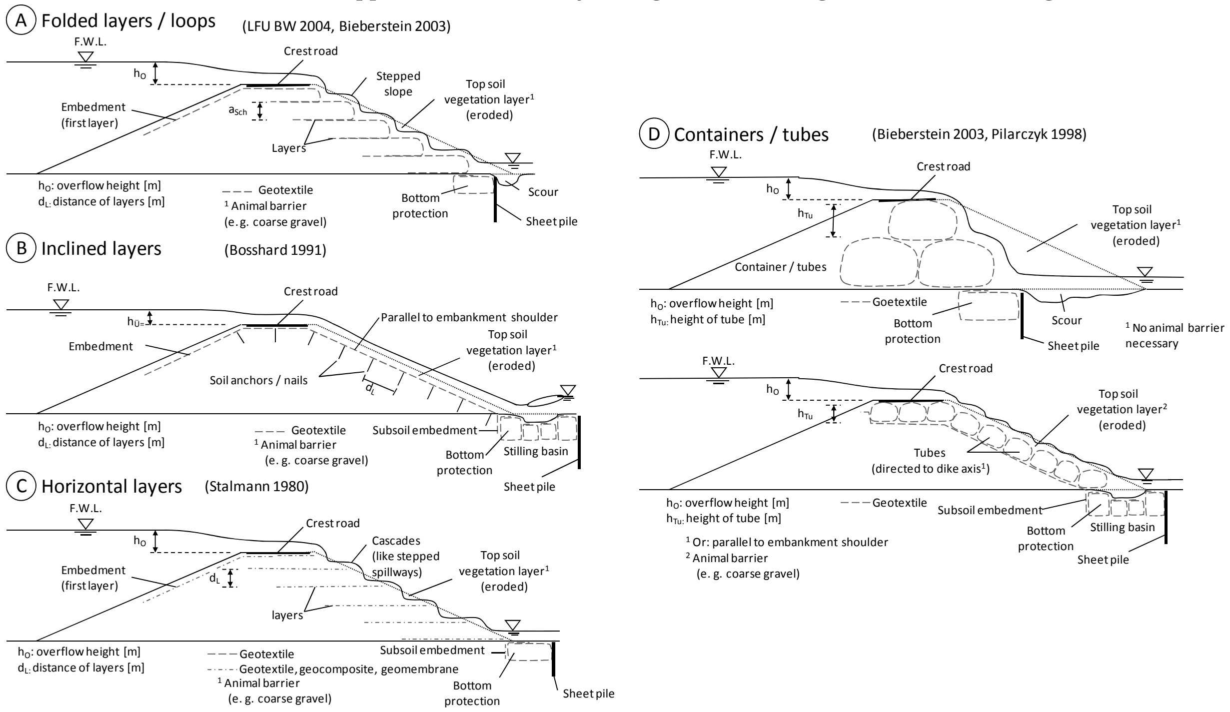

Figure 2. Typical overflow protection systems of flood embankments using geosynthetics (Haselsteiner et al. 2007a)

Overflow tests and results

At the laboratory of the Institute of Hydraulic and Water Resources Engineering a series of model tests were carried out in the years of 2006/07. Two of the examined constructions that performed best are shown in Figure 3 and Figure 4. The test rig was located in a concrete U-profile discharge section of 2.5 m width and 2.5 m height. Therefore the tests were carried out in full scale. The test rig channel was about 20 m long. The models were loaded by specific discharge values from 0.050 m³/s/m up to 0.300 m³/s/m which lead to overflow heights of 0.10 m to 0.35 m. The water was stored in a reservoir upstream from which it was pumped into the test rig. A more detailed description of the test model and the test series is given in Haselsteiner et al. (2007b).

Applying a composite product of a geotextile and a geogrid the system shown in Figure 3 performed well. Underneath the surface protection layer, gravel was spread and compacted. The transition zone from sand body to gravel layer was filtered by a geotextile filter. To provide homogenous overflow conditions a steel kerb was placed on the crest. The system performed well, even when the number of anchors were reduced step by step. A symmetric, “loosen” arrangement of the anchors provided sufficient stability. Though, in two tests one single anchor near the dike bottom failed, the stability of the whole structure was not endangered. One advantage of this kind of protection system for practical use is the simple way of application. After the refurbishment of dikes, the geosynthetic layer can easily be placed on the finished landside slope. The top soil layer can be placed on the top of it afterwards.

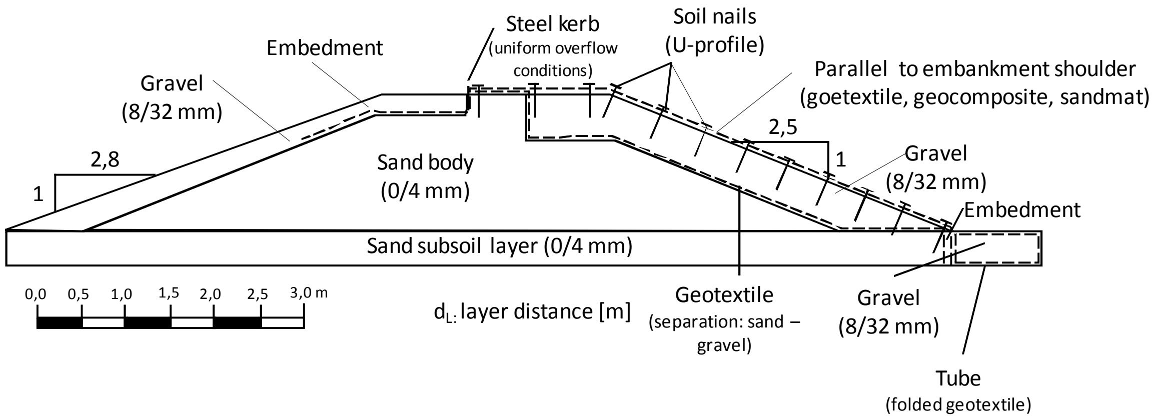

Figure 3. Dike model with layers parallel to embankment shoulder fixed by soil nails (Haselsteiner et al. 2007b)

The system using folded layers or loops has the advantages that a certain part of the energy dissipation takes place on the slope similar to stepped spillways. Furthermore, the closed form prevents all kind of soil particle transportation due to seepage flow and overflow. Among the investigated systems the folded layers are considered to have most bearing capacity. During earth moving works the construction of the loops can easily be synchronised with the spreading and compaction of the soil layers.

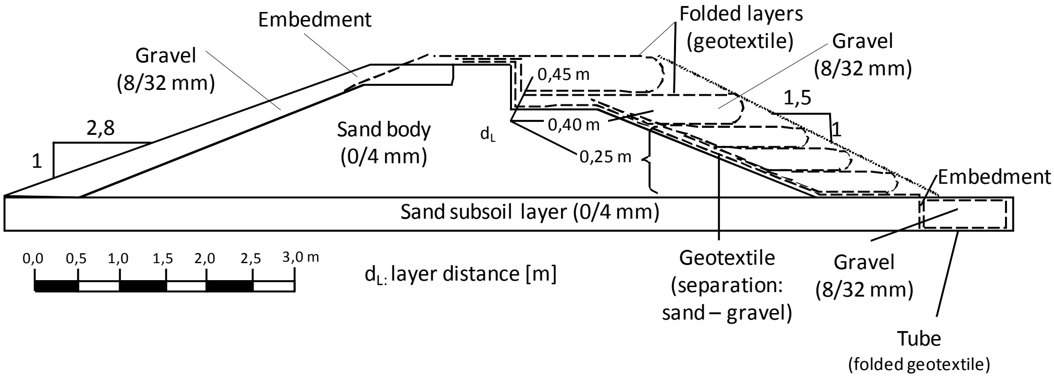

Figure 4. Dike model with folded layers/loops (Haselsteiner et al. 2007b)

Pictures of both protection systems for unloaded and loaded conditions are presented in Figure 5. Both systems performed well when loaded by a specific discharge of 0.130 m³/s/m. It can be seen that deformations were little and no remarkable damages occurred to the systems.

Figure 5. Loaded and unloaded dike models with slope parallel geosynthetic layers using anchors for fixation (left) and horizontal, folded layers (loops) (right) (Haselsteiner et al. 2007a, b)

Static model and recommendations

The loads onto the protection systems are created by earth pressure, by seepage and overflow forces. Whereas earth pressure and seepage forces are more or less static forces which can be sufficiently determined by simple assumptions, the dynamic forces of the overflow jet which may perform like a stepped spillway jet (Figure 6) is more difficult to determine. To investigate the External and Internal Stability of geosynthetic protection systems the definition of a static model has to be created. Whereas, the resistance parameters of the soil in combination with geosynthetic reinforcement layers are described very well in literature (Saathoff & Zitscher 2001, DGGT EBGEO 1997), the impact of dynamic hydraulic loads on earthen, reinforced structures are poorly investigated. Analogies however can be found in similar loaded structures as stepped spillways or chutes. Nevertheless the determination of design loads has to be conducted conservatively. This may contain a sufficient factor of safety for the structure. But for efficient and economical designs the authors are convinced that more and detailed research work has to be carried out.

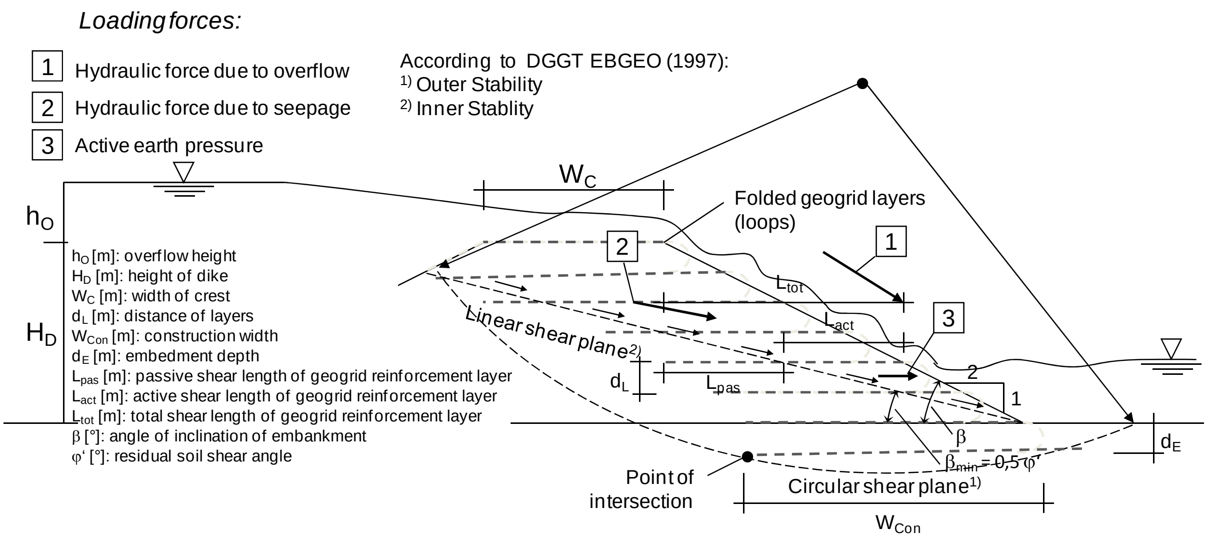

Figure 6. Static model for reinforced overflow embankments (Haselsteiner et al. 2007c)

BENEFITS

Benefits occur both because of lower construction costs and because of the avoidance of dike breaches and flood damages. Whereas the avoidance of damages is an advantage of all overflow protection systems using e. g. riprap or asphalt (LFU BW 2004) reinforced slopes provide a very cheap solution as it is shown below (Figure 7).

Benefit of construction

By using geosynthetics as soil reinforcement, steeper slopes can be applied. In case of overflow protection systems this is a fundamental benefit because comparable solutions need slope inclinations of V:H = 1:4 and flatter. In Figure 7 the benefits, costs and savings of a reinforced embankment are given for different dike heights and are compared to dikes with usual slope inclinations consisting completely of soil material. The dike parameters are added in Figure 7, too. The fact that this design performs simultaneously as an overflow protection system is neglected within this analysis. It is shown that the savings of earth works exceed the costs for the geosynthetics at dike heights of over 2.0 m.

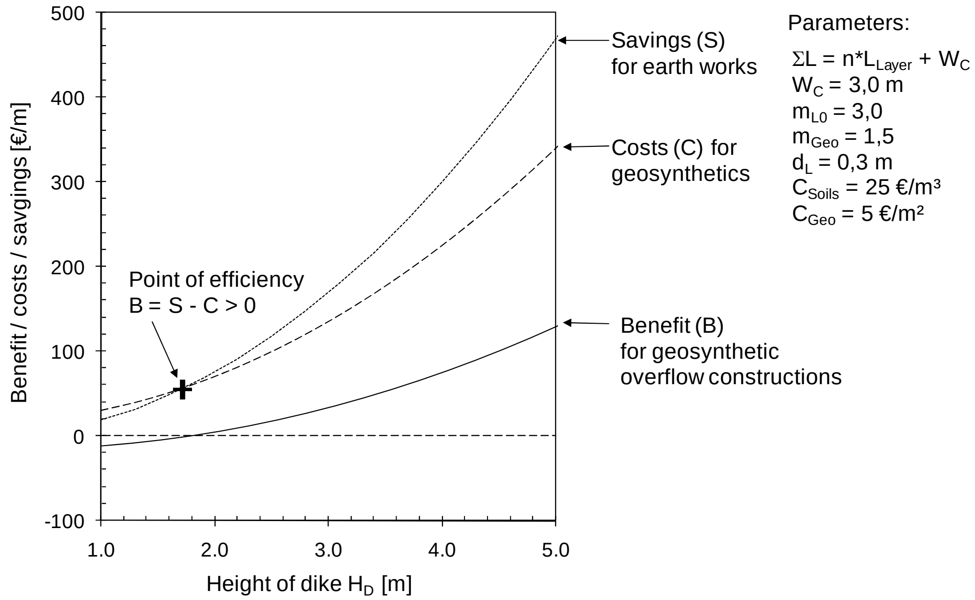

Figure 7. Benefits, costs and savings for embankment overflow constructions using geosynthetics (Haselsteiner et al. 2007c)

The economical advantages of geosynthetic overflow protection systems become obvious when different protection measures / systems are compared (Figure 8). Riprap structures will roughly produce 30 % more costs. Flatter slopes inclinations with a top soil vegetation layer as erosion protection multiply the costs compared to geosynthetic solution because more construction work has to be done. With rising dike height and rising volume of the dike body the cost difference between the methods increases, too.

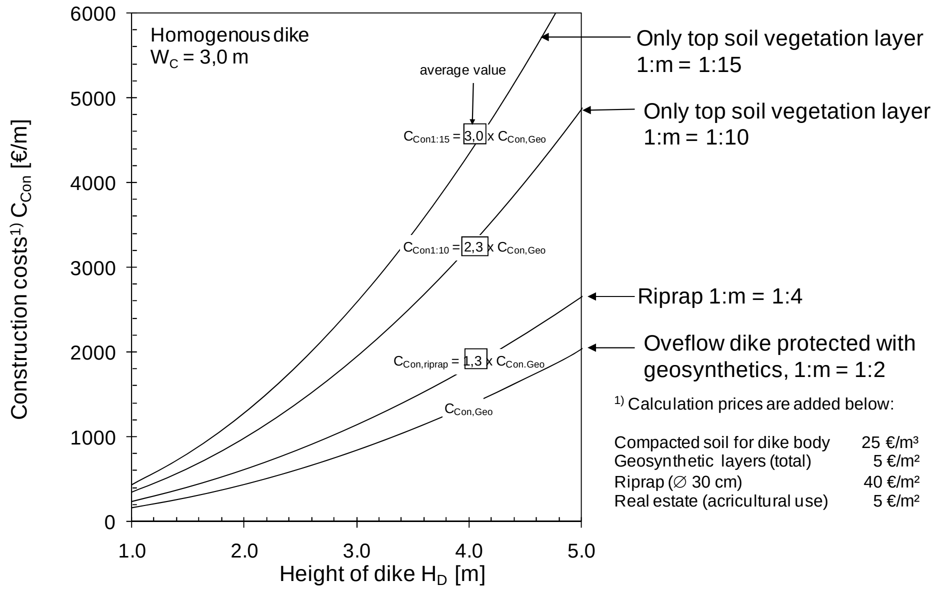

Figure 8. Construction costs for embankment overflow constructions using compared to constructions using rip-rap or flatter embankment inclinations (Haselsteiner et al. 2007c)

Benefit of avoiding flood damages

The fundamental reasons for overflow protection structures is reduction of flood damages by retarding of flooding, by avoiding of a sudden dike breach, by avoiding of subsequent flood waves and (re)activating of flood retention volume. The latter reason effects mainly downstream discharge and water level conditions, thus no direct benefit to the goods, human beings or livestock in the hinterland. Flood retention systems with overflow dikes are generally located in agricultural areas with low or no damage potential. In areas with high damage potential, the effects of flooding retardation and avoidance of dike breaches contribute to reduce the flood risk.

In these areas, overflow protection systems at dikes may just mitigate extreme flood events that are more unlikely to occur than the design flood. Therefore the polder achieves additional safety in case of the water level exceeding the dike crest and flooding begins. Depending on topography and duration of a flood incident, the hinterland is flooded very slowly compared to dike breach sceneries. This retardation can be roughly estimated by the consideration of a simple flood model, calculating polder discharge by common discharge formulas according to POLENI and comparing different overflow heights. The geosynthetic reinforced overflow dike simply has to withstand a discharge caused by a 0.30 m high overflow. An unprotected dike however, will fail, and then the discharge height will be equal to the dike height plus 0.30 m. In Figure 9 an example for this retardation effect is given.

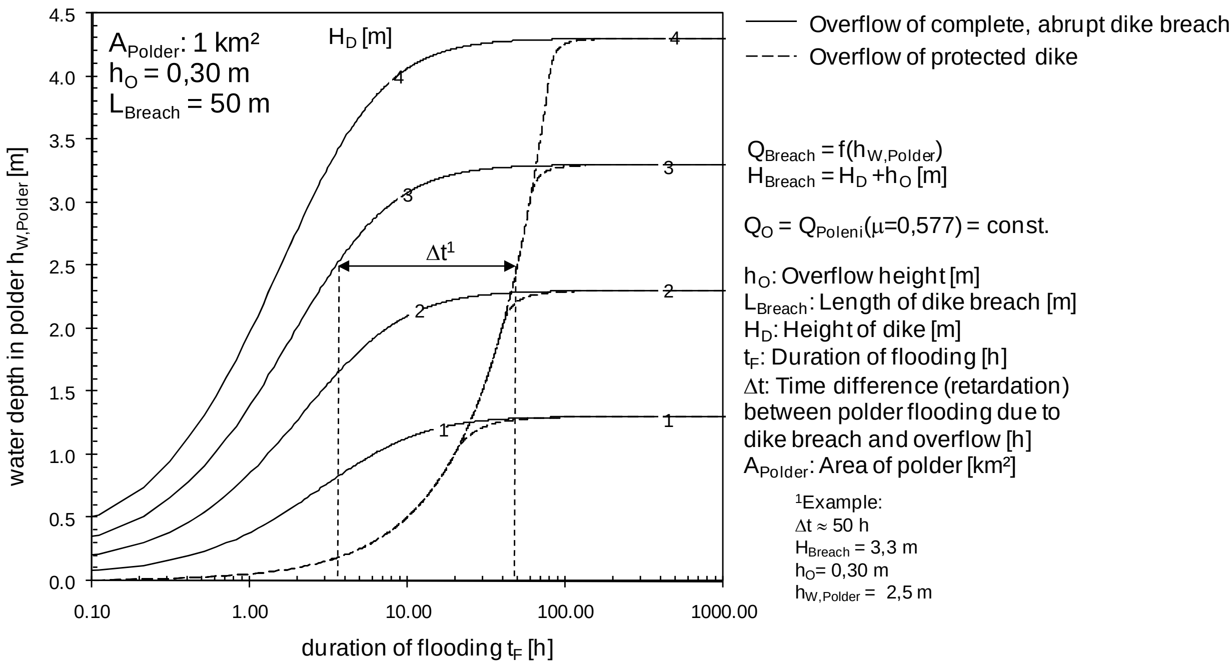

Figure 9. Water depth in polders in relation to flood duration for protected overflow dikes and breached dikes (Werth et al. 2007)

A dike failure causes rapid flooding of the polder, which is accelerated by higher water loads for higher dikes. For overflow dikes on the other hand, the discharge does not depend on the height of the dike, but only on the overflow height. When the water level in the flooded hinterland reaches 2.5 m the retardation becomes about 50 - time for task forces to evacuate livestock or for impacted inhabitants to carry out local flood protection measures.

Keeping in mind that floods are only temporary incidents, the following effects can be explained. Short lasting flood incidents often occurring at typically alpine rivers, only cause very low water levels in the polder. Taking into account a flood duration time of 10 h the water level of the example given in Figure 9 reaches just a level of about 0.30 m.

Long lasting incidents at protected overflow dikes with durations of one week or more will result in the same high water levels as caused by dike breaches. Thus, at huge rivers with long lasting flood incidents, e. g. the Danube, the Elbe or the Rhine in Germany, the damage reduction is not produced by low water levels but by flood protection action during retarded flooding processes. The damage potential can be reduced e. g. by removal of goods. In Figure 10 these effects are expressed by the dashed lines. The final reduction of the damage potential reaches a value of 0.33 in the presented example.

This theoretical example illustrates the effects of overflow protection systems along rivers. Here, both benefits during construction and flooding were investigated separately and the authors think that both each advantage for itself justifies a structural realization within flood protection measures.

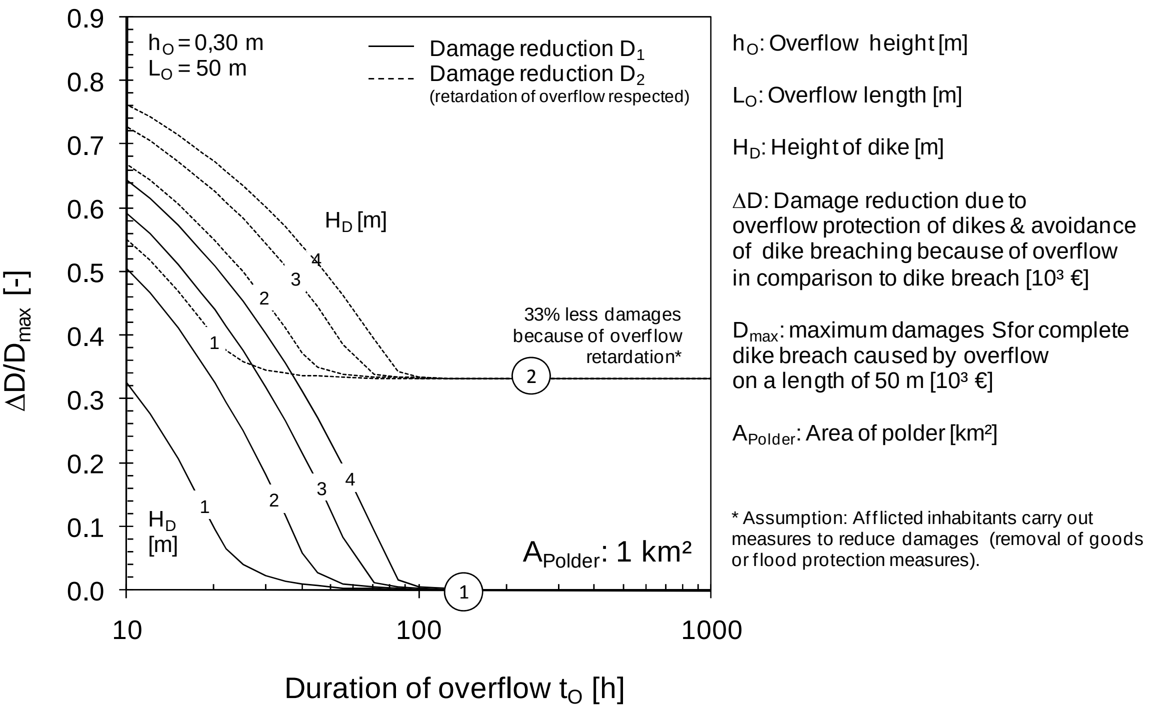

Figure 10. Damage reduction of protected overflow dikes related to duration of flooding (Werth et al. 2007)

CONCLUSIONS

Overflow protection systems within flood embankments are an efficient method to reduce vulnerability, risk and damages of concerned hinterlands. Especially rural areas with high damage potential bear applications for this construction method. Among all technical solutions for designing overflow sections, the use of geosynthetics seems to be the most economical way of providing a safe and durable structure. As the advantages are so clear soon design schemes, specifications and standard layouts will be developed and the first application in practice will be done.

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