Levee Protection and Crest Stabilisation with Geocells

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ABSTRACT

Based on observations and analysis of the last flood disasters in Germany, one of the main reasons for heavy damage of levees lies in the temporary overtopping of them. At the air-side slope and the crest of the levees erosion processes, which come along with the overtopping, cause local or global failure in the worst situation. At the same time the water level and flow velocity increase steadily due to climate change, so that the interest in purposely overtopping of levees into polders grows. In order to prevent any damage, the levees have to be built stable against erosion. There are already some constructional solutions, e.g. rock fill, stone pavement, the use of geosynthetics or soil stabilisation. Yet most of them do not provide sufficient stability against surface erosion during overtopping and/or fail due to the lack of erosion stability against water outflow at the air-side slope. As a consequence they are limited in their field of application (e.g. max. allowable flow rate). Alternatively a sealing is often placed at the air-side of the levees so that erosion is prevented. These sealings, however, can result in an impermeability of the slope and the water seeping through the levee is collected below it. In some cases this can lead to massive damage of the sealed levees. Besides the description of the limitations of existing constructional solutions, the principle and expected advantages of geocells applied as overtopping protection system are introduced. It is believed that this system is capable to provide stability against erosion and improves the bearing capacity of the soil simultaneously.

Keywords: overtopping protection systems, levee stabilisation, application of geocells

1 INTRODUCTION

In future the results of climate change will require new engineering solutions for levees and embankments located at riversides. Increasing water levels and flow velocities of rivers can be expected as a result of the climate change. Consequently, the frequency and magnitude of flood events will dramatically grow. These events will lead to new requirements on the durability and stability of the levees and embankments. In most cases, however, it is not practical to steadily adjust the flood protections (e.g. raise of the dam crest) to the changing requirements from an economical and technical point of view (Blovsky 2009). For this reason, the construction of erosion-resistant levees with polder areas, where floods can be discharged without any risk, will become more and more important in the near future.

An investigation of the last flood events shows that levee failure, especially for overtopping, mainly develops from the air-side slope (Werth et al. 2007). In case of long-lasting or recurrent overtopping, the bottom shear stress caused by the overtopping water can result in erosion processes at the crest or the air-side surface of the slope. If stabilisation of the damaged crest or slope is not possible, a further overtopping can trigger a collapse of the whole levee or embankment. Then the flood water cannot be discharged under controlled conditions and a risk to the surrounding regions arises.

Figure 1 shows a levee failure due to a flood event near Laußig in Saxony in the year 2002. An analysis of Heyer and Horlacher (2007) from the Technical University of Dresden demonstrates that approximately 60 percent of the levee failures were caused by overtopping water during the flood event.

Besides the surface erosion-related failure of a levee due to overtopping, the water flowing through the soil body poses another risk to the stability of the air-side slope. The infiltrating water and the water seeping from the river-side to the air-side can significantly reduce the factor of safety against local and global failures at the air-side slope. Therefore, the risks of a sliding revetment or a slope failure increase considerably (Steuernagel 2008). So the installed constructional solutions must maintain sufficient stability even when very different load combinations act, as it is the case in many overtopping problems. This requires stable overtopping protection systems, which are capable of preventing any surface erosions of the air-side slope and simultaneously provide convenient hydraulic efficiency and stability against inner erosion processes. Then, the development of pore pressure beneath the revetment and erosion-related outflow of soil particles is avoided. Another important fact is the inaccessibility of the crest or the dike protection path after flood events. As a result of the overtopping water, the ground softens and the bearing capacity decreases dramatically. Consequently, reparation work of damaged levees or embankments is slowed down or even made impossible. In some cases this can lead to progressive damage of the levees and eventually a global failure.

Figure 1. Levee failure at the river "Vereinigte Mulde" near Laußig in Germany, 2002 (Heyer 2007)

2 EXISITING OVERTOPPING PROTECTION SYSTEMS

There are a huge number of constructional solutions for overtopping problems. A selection of the most important protection systems and their limitations in application are presented subsequently.

2.1 Stone pavements (Figure 2):

The use of unbonded stone pavements at the air-side slope is only suitable for slopes with inclinations up to 1:6 and a maximal flood flow rate of 1.0 m^3/s. As a consequence of the small interlocking effects of the unbonded stone pavements, single stones can be detached and a failure of the whole revetment can emerge. Compared to the unbonded systems, the allowable inclination of bonded stone pavements is higher. Yet, the installation of the bonded systems is more time-consuming. In spite of this, the lack of flexibility of the bonded stone pavements is another disadvantage. Due to the missing flexibility, displacements can result in seepages at the revetments and further erosion processes. Another disadvantage arises from the sealing effects of the bonded systems, because the impermeability of the bonded systems decreases the factor of safety against lifting of the revetment.

2.2 Loose riprap (Figure 3):

The maximal inclination of systems with loose riprap is limited to 1:4. As for stone pavements the maximal flow rate is 1.0 m^3/s. A sufficient layer thickness of the riprap must be considered. The allowable thickness $d_{b,min}$ depends mainly on the maximum grain diameter d_{100} of the riprap and is derived from the equation $d_{b,min} = 1.5 \cdot d_{100}$. The most important advantage of this solution is the fast and easy installation. In contrast, the interlocking effects of this system are even weaker than those of the unbonded stone pavements. Thus single stones as well as entire stone formations can be detached during overtopping events. Considering the durability of such systems, small changes in the flow rate and flow through of the soil body could yield in relocations of the riprap material. With these relocations, the development of erosion pipes is likely to happen.

2.3 Geogrids (Figure 4):

The installation of geogrids parallel to a slope should only be carried out, if the inclination of the slope is less than 1:6. Here the maximal flow rate should not exceed 1.0 m^3/s. Because of the difficulties to achieve a sufficient interlocking between the body of soil and the geogrids, the most frequent failure of these protection systems is the sliding of the entire revetment. Furthermore, the utilisation of cover layers above the geogrids is necessary against strength-reducing UV-radiations. Another dis-advantage results from the lack of sufficient filter stability of some geogrids products. So additional measures must be adopted, which can cause high additional cost. As long as properly installed, overtopping systems with geogrids show a reliable long-term performance and high resistance against tensile forces, which are induced by the bottom shear stresses of the overtopping water.

2.4 Open stone asphalt (Figure 5):

Here, the minimal layer thickness is 13 cm. Then the air-side slope can be inclined up to i = 1:6. As in the other overtopping systems, the maximal flood flow rate must be less than 1.0 m^3/s. If the flow rate exceeds this threshold, a slip of the filter layer and the open stone asphalt layer becomes very likely. The high interlocking effect with the revetment, the good drainage performance and the coherent behaviour are the biggest advantages of this protection system. High material costs for thicker layers and a high impermeability are the negative effects of this constructional solution. Because of the high impermeability the failure of lifting must always be considered.

2.5 Soil stabilisation (Figure 6):

The limitations for conventional soil stabilisation are a compacted layer thickness from at least 1 m or a multilayer compaction (DVWK 1991), a maximal inclination of 1:4 und a restriction of the maximal flood flow rate to 1.0 m^3/s. The compaction of the air-side slope can result in areas with different levels of compaction, for example, when the underground consists of various types of soil. So the risk of local failures or sliding will be higher. Another disadvantage comes from the fact of the sensitivity of the compacted soil against weather influences. However, the improved strength properties due to the improved bulk density lead to increased stability against erosion processes.

2.6 Sandwich constructions by geosynthetics (Figure 7):

In sandwich constructions the geosynthetics (e.g. geogrids, geotextiles) serve as reinforcing elements. By absorbing tensile forces and stabilising the soil layer between two geosynthetics, the strength of the whole levee body is significantly increased. Folding of the geosynthetics at the air-side slope improves the stability of the levee material. Depending on the type of sandwich construction, there are different limitations of the allowable slope inclination and flood flow rate. In case of overtopping, the increased forces acting on the air-side slope can cause a detachment of single geosynthetics as well as a detachment of the entire segments. The biggest advantage of these overtopping protection systems is the variability of the cross sections due to a very steep construction of the air-side slope. The fact, that the sandwich construction in conjunction with geosynthetics can be only used for newly constructed levees or slopes, can be considered as the most important disadvantage (LfU BW 2004).

Figure 2. Stone pavement

Figure 3. Loose riprap

Figure 4. Geogrids

Figure 5. Open stone asphalt

Figure 6. Soil stabilisation

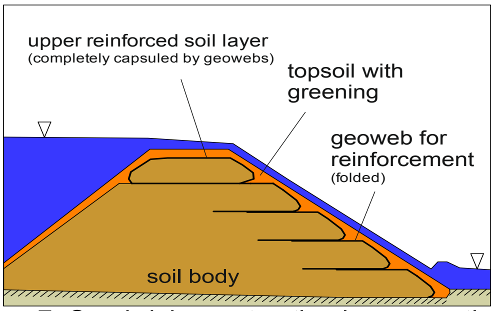

Figure 7. Sandwich construction by geosynthetics

Figure 2 - 7. Overtopping protection systems (LfU 2004)

The above mentioned overtopping protection systems are usually used as an alternative to a conventional flattening of slopes. Here stability against erosion is ensured by the greensward planted at the air-side slope. Besides all these partially permeable protection systems, it can be an economical solution to install sealings (e.g. synthetic geomembranes) sometimes. Yet, these impermeable solutions carry certain risks, since the seeping water can accumulate beneath the sealing. As a result, lifting forces can cause local or global failure of the air-side slope (Akkerman et al. 2007). Another failure mechanism can be triggered by installing geocomposites as overtopping protection systems. Werth et al. (2007) showed in several overtopping tests, that, even for proper installed geocomposites, the soil beneath the air-side top layer is eroded and the entire revetment can fail.
So far, it can be seen that none of the presented systems is suitable as an overtopping protection system without certain limitations. The use of geocells could be a simple and stable solution to meet all the necessary requirements for overtopping problems.

3 GEOCELLS AS PROTECTION SYSTEM

3.1 Protection against erosion

Geocells are single, three-dimensional synthetics, which are joined by means of several production processes in order to form a comb-shaped bearing system. These bearing systems are installed and filled on site. The walls of the cells hold the fill material in position and prevent horizontal displacement during vertical loading. Additionally, the force-deformation behaviour and the bearing capacity of the soil are significantly improved. Geocells are usually used as a fast and cheap alternative in road construction engineering to increase the stability of less sustainable ground. While the application of geocells used to be limited mainly to road constructing in the past, they also gain importance in different fields of application nowadays, for example in dam and embankment constructing. Here they do not only serve as protection against erosion, but also to ensure sufficient trafficability of dike defence paths or roads at the crest of a dike (Meyer and Emersleben 2009).
The application of geocells for overtopping protection benefits mainly from their ability of increasing resistance against the downslope erosion forces resulting from the overtopping water. The comb-shaped structure of the geocells ensures the stability of the fill material in each cell and prevents its downslope displacement (Figure 8). The prevented displacement of the soil causes tensile forces, which are absorbed by the walls of the geocells and the friction between the geocell layer and the soil body. In addition, the geocells can be fixed and stabilised with anchor rods and wires (Figure 9). A high permeability of the geocell walls can be achieved by perforating them. So a free drainage of seeping or overtopping water is possible, while holding the fill material in position.

Figure 8. Installed geocells at a slope (RKL)

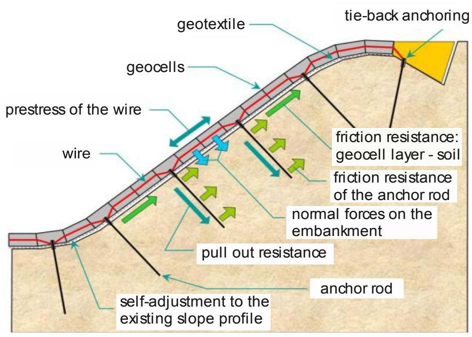

Figure 9. Erosion protection with geocells

Usually, ordinary fill materials are limited in their suitability for overtopping protection systems. The forces acting during overtopping can cause a washout or undermining of the fill material in the geocells. In 2006, overtopping performance tests of geocell reinforced air-side slopes were conducted at the Engineering Research Center Fort Collins of the Colorado State University. During each performance test, the flow rate Q was stepwisely increased from 0.42 m^3/s to 3.07 m^3/s within 1 hour. In the first tests the geocells were filled without any additional measures. After the test, a significant material loss due to the erosion of the fill material was observed. Therefore, vegetated geowebs were installed above the reinforced geocells in the subsequent performance tests. As a consequence, the amount of eroded material decreased and the overall performance of the entire protection system was clearly improved. Nevertheless, local erosion of the fill material could not be prevented in some areas (Clopper et al. 2006).
Since the fill material already erodes in some areas after overtopping intervals of one hour, it is likely that long-lasting or recurrent overtopping events could lead to highly developed and more uncontrollable erosion effects. It is clear to see that natural materials, like gravel or coarse sand, are not suitable to provide sufficient stability against erosion, despite their good draining abilities. Alternatively concrete could be casted into the cells. The concrete in the cells would ensure good stability against erosion. But still the disadvantage of the high impermeability would not be solved. For this reason, the development of a drainable material with a simultaneous stability against erosion is planned.

3.2 Improved bearing capacity

The overtopping of levees and embankments results in softening of the soil at the levee crest and the air-side levee toe. As a result, the bearing capacity of these areas is reduced significantly, so that accessibility cannot be assumed anymore. Geocells can be used to provide permanent access to the levee, even for destabilised ground conditions. Dash et al. (2001) and Emersleben and Meyer (2007) showed in several tests, that the bearing capacity of the soils reinforced with geocells is two to four times the bearing capacity of unreinforced soils. In contrast to geogrids, where the reinforcing effect is mainly based on interlocking, passive earth pressure and friction, the bearing capacity of Geocells is a result of hoop stresses in the wall elements, lateral bedding from the adjacent cells as well as mobilised friction between the fill material and the wall elements (Emersleben 2010). The described bearing mechanism of geocells is schematically depicted in Figure 10.

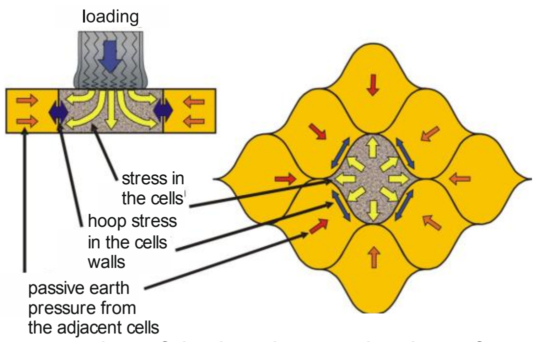

Figure 10. Schematic representation of the bearing mechanism of geocells (Emersleben 2010)

During loading, the hoop stresses as well as the lateral bedding mobilise additional shear strength in the fill material. This fact was proved by triaxial tests of single geocells by Rajagopal et al. (1999). From the results, it was shown that the geocells induce a type of apparent cohesion in the fill material. As a consequence, an increase in the stiffness and an improvement of the load-deformation-behaviour of the reinforced layer are generated in the reinforced layer. Especially when using geocells in less sustainable ground conditions, the reinforced layer acts as a stiff, load distributing plate, which reduces vertical displacements (Meyer and Emersleben 2006). When the system of geocells and fill material is loaded up to the limit state, the geocells stops the forming of shear planes in the reinforced layer. Therefore, the shear planes shift in a greater depth and the safety against bearing failure is significantly increased (Guido et al. 1989).
In order to provide sufficient bearing capacity for the entire levee, the geocells can be installed at the air-side slope, the air-side levee toe and the crest of the levee. Thus the levee would be permanently trafficable at the crest and the dam protection path, if existing. In case of floods or after overtopping it could still be possible to gain access to the affected areas and accomplish levee protection measures

(Figure 11). Moreover, the installation of geocells is also conceivable to allow using of the crest as a regular road in cases of insufficient soil conditions (Figure 12).

Figure 11. Softened levee toe

Figure 12. Geocells at the crest of an embankment

4 CONCLUSION

By analysing existing overtopping protection systems, it was shown that they are limited in application in most cases. The special requirements for protection systems can make them ineffective or uneconomical. Therefore, the development of a new overtopping protection system is in progress, which also takes into account the increasing frequency and magnitude of flood events in future. The principle and expected advantages of geocells as overtopping protections were introduced in this paper. Besides its capability to increase the bearing capacity even for weak soils, it can also provide erosion resistance for the fill material. The common fill materials, however, do not completely meet the necessary requirements, so that a new drainable and erosion-resistant material has to be developed. In addition, the increased bearing capacity can be used to ensure accessibility to the levees even after overtopping or to provide sufficient bearing capacity for road constructions. In order to proof the above mentioned advantages, several performance tests with different fill materials are carried out at the moment, but cannot be presented yet.

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