Hydraulic failure of flood protection dykes

Défaillance du circuit hydraulique des levées de protection contre les inondations

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ABSTRACT: The increase in frequency, magnitude and duration of floods during the past decades has become an outstanding challenge to geotechnical engineering. Appropriate measures against hydraulic fracture due to underseepage of dykes or levees require comprehensive knowledge of failure modes. This paper describes various forms of hydraulic failure and its critical values for different types of soil. Furthermore, measures to prevent hydraulic failure by placing berms or by installing relief elements at the landside dyke toe are discussed.

RÉSUMÉ : L'augmentation de la fréquence, l'ampleur et la durée des inondations au cours des dernières décennies, est devenu un défi exceptionnel à la géotechnique. Des mesures appropriées contre la fracturation hydraulique en raison de l´écoulement phréatique de barrage de rivière ou levées nécessitent une connaissance approfondie des modes de défaillance. Cet article décrit les différentes formes de défaillance du circuit hydraulique et de ses valeurs critiques pour différents types de sol. En outre, des mesures pour prévenir une panne hydraulique en plaçant des bermes ou en installant des éléments de relief à l'orteil terrestre digue est discuté.

KEYWORDS: dykes, flood protection, hydraulic failure, uplift, relief drainage.

1 INTRODUCTION

Floods have affected millions of people worldwide in recent decades. In several regions the magnitude and frequency of flood waves have increased dramatically since long-term measurements and historical reports have existed. In Austria, for instance a 2000 to 10 000-year flood event was back-calculated from the flood disaster in the year 2002. Such hitherto singular values cannot be taken as design values for flood protection dykes, but they underline the need for local overflow crests or spillway sections. Moreover, they clearly demonstrate that a residual risk is inevitable – despite most costly protective measures.

The risk of dykes or levee failure increases not only with the magnitude of a flood but also with its duration. For instance, the peak period of flood waves along the Austrian section of the river Danube usually lasts one to three days, whereas its tributary, the river March/Morava (Austria/Slovak border) frequently undergoes flood waves up to three or six weeks (Fig. 1). Figure 1 also illustrates the increase of magnitude and frequency of the floods since the 1990s.

Especially long-lasting flood waves exhibit in combination with a required groundwater communication below dykes a high risk potential regarding hydraulic failure. But also periodic short hydraulic loadings of flood protection dams and their subgrade can produce a failure caused by an inner erosion processes in a long-term.

2 FAILURE MODES OF DYKES

The knowledge of possible failure modes is an essential prerequisite for a reliable quality assessment of existing dykes and levees, and for an optimized design of new ones and for rehabilitation work. Moreover, it helps to optimize emergency measures during flood defence.

The dominating failure modes for typical ground conditions along rivers (near-surface, low-permeability sandy to clayey silts underlain by high permeability sand or gravel) are:

- overtopping or overflowing of the dyke/dam crest,
- hydraulic fracture,
- surface erosion and failure of the water-side slope due to wave action,
- piping due to animal activities, especially from beavers and rats,
- slope failure due to excessive pore-water pressures, seepage or inner erosion,
- slope failure due to a rapid drop of the flood water level,
- unsuitable planting of dykes (especially trees with flat roots).

Actually, it is often difficult to precisely determine the causes of a dyke failure. Several types of processes might be involved in a breach and multiple modes in a dyke failure. Statistical analyses show that overtopping and internal erosion are the most common modes of failure. While many of these failure mechanisms occur relatively fast, the erosion by underseepage develops more inconspicuously. If a groundwater communication below the dyke is possible, the aquifer or the overlaying low permeable layer can be progressively eroded during hydraulic loading. Hydraulic failure is critical because there may not be any external evidence, mostly only soil boiling can be found.

Due to this unpredictable behaviour hydraulic failure is frequently underestimated in practice and may occur in different forms (e.g. Eurocode 7; CEN 2004):

- By uplift (buoyancy). The pore-water pressure under the low-permeability soil layer exceeds the overburden pressure.
- By heave. Upward seepage forces act against the weight of the soil, reducing the vertical effective stress to zero; soil particles are then lifted away by the vertical water flow.

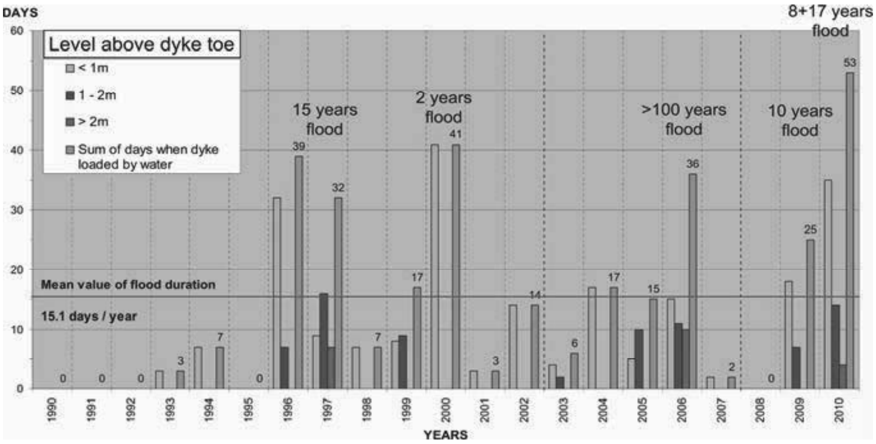

Figure 1. Duration of floods along the River March dykes (Water level at Dürnkrut – Austria/Slovakia; adapted after via donau). Two floods within three weeks in 2010.

This ‘boiling’ dominates in silty-sandy soil, and is combined with internal erosion.

- By internal erosion. Soil particles are transported within a soil stratum or at the interface of soil strata (Fig. 2). This may finally result in regressive erosion, leading to ground failure of the dyke, levee or dam.
- By piping. Failure by piping is a particular form of internal erosion, where erosion begins at the surface, and then regresses until a pipe-shaped discharge tunnel is formed. Failure occurs as soon as the water-side end of the eroded tunnel reaches the river bed or bottom of the reservoir. Frequently, several tunnels develop. This process may be induced or significantly promoted by animal activities, as field observations over many years have revealed.

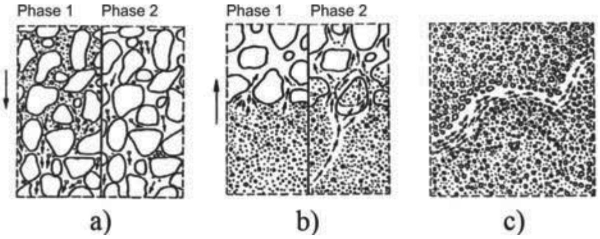

Figure 2. Hydraulic fracture of dykes or flood protection dams due to seepage through or beneath the dyke or dam (Ziems 1967): (a) suffusion (fine particles move into pore voids of coarse grain fractions); (b) contact erosion at the interface of soil strata; (c) internal erosion in steady-state flow condition.

Hydraulic failure may reach several tens of meters away from dykes or dams, as experience has shown (Fig. 3). This could be observed even for low flood protection embankments with a relatively small hydraulic gradient.

Eurocode 7 (CEN 2004) states that in situations where the pore-water pressure is hydrostatic (negligible hydraulic gradient) it is not necessary to check other than for failure by uplift. In the case of danger of material transport by internal erosion, filter criteria should be used. If the filter criteria are not satisfied, it should be verified that the critical hydraulic gradient is well below the design value of the gradient at which soil particles begin to move.

Experience has shown that the magnitude of the critical hydraulic gradient where internal erosion begins is frequently overestimated. Figure 4 summarizes the critical values on the basis of field observations, geotechnical measurements, literature and long-term experience for different soils. For comparison, the conventional criterion ($i_{crit} = \gamma\,'/\gamma_W$), Lane’s criterion, and the critical zones after Eurocode 7 (CEN 2004) or Chugaev (1965) respectively are also plotted in the diagram.

Figure 3. Piping (soil boiling) far away from the dyke, and stabilizing measures to reduce the hydraulic gradient (photo: L. Nagy).

Hydraulic failure may occur despite cut-off walls, if they are “imperfect” walls in order to allow groundwater communication below the dykes or levees (for environmental reasons). Fine-grained cover layers with local “windows” and low residual shear strength favour such failure modes.

The need of underseepage control for permanent or temporary hydraulic loaded dams or levees is determined from the ground profile, soil mechanical properties and hydrological parameters. Seepage enters the permeable aquifer through the riverbed and through cracks and inhomogeneities in the waterside near-surface cover layer. Due to the hydraulic gradient the groundwater flows from the riverside to the landside of the dyke. This results into an artesian head at the base of the landside low permeable soil layer during the sustained flood stages. The overpressure may cause sudden uncontrolled heave or rupture of the landward fine-grained cover layer, especially at the dyke toe, followed by concentrated seepage flow and erosion in this area. If the seepage through the cover layer is possible then the hydraulic failure may occur without heaving and only through erosion of the fine-grained soil. The suffusion process is usually accompanied by piping of the aquifer and causes a gradual safety reduction.

Consequently, for the underseepage of dykes or levees safety analyses regarding hydraulic failure by erosion and/or heaving of the cover soil layer have to be performed.

Filter protection against hydraulic failure at the embankment toe is generally provided by the use of non-cohesive granular material (natural soil) that fulfils adequate design criteria for filter materials. Filter geotextiles have been

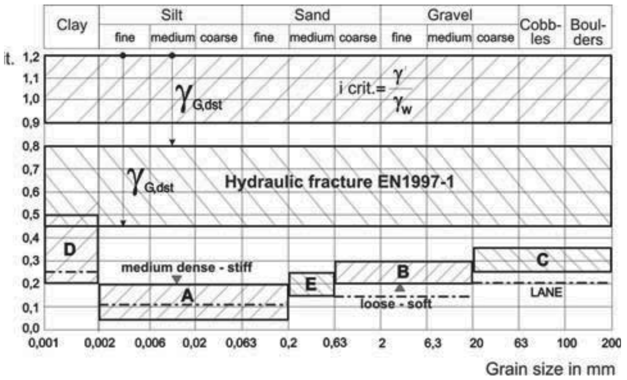

Figure 3. Critical hydraulic gradients for hydraulic fracture (internal erosion) (Brandl and Hofmann, 2006); $i_{crit.}$ depends not only on grain size distribution and density/stiffness but also on flow pressure; $\gamma_{G,dst}$ = partial safety factor for permanently unfavourable effects.

used increasingly since the early 1970s. Common filter criteria for soils are from Terzaghi and Sherard, and for geotextiles from Giroud (2010) and Heibaum et al (2006). All criteria have particular limitations, whereby non-cohesive and cohesive soils have to be distinguished. While two criteria are sufficient for granular filters (the permeability criterion and the retention criterion), four criteria are required for geotextile filters (Giroud 2010): the porosity criterion and the thickness criterion also have to be considered.

3 MAESURES AGAINST HYDRAULIC FAILURE

Hydraulic failure as an effect of underseepage may be prevented mainly by two permanent measures landward of a dyke or flood protection dam by

- installing trenches or relief columns or drainage wells,
- filling of berms, thus displacing the possible starting point of inner erosion or piping further away from the structure, and decreasing the hydraulic gradient at this point. Such berms should be constructed as access roads for quick and easy dam defence in the case of severe floods.

The function of the berm is to compensate through its counterweight the pressure which is acting at the base of the cover layer (Fig. 4a) and to prevent hydraulic failure of the dyke by seepage or uplift, or by internal erosion and piping. At the same time it must allow a free water outflow. Otherwise an excessive pore-water pressure would cause a sudden failure. Filter stable berms (filter geotextiles covered with sand, gravel, or other granular material) are often used as an emergency measure, when seepage occurs.

In many cases berms merely move the hydraulic problem further away from the dyke or dam, and retrogressive inner erosion may finally reach it in the long term (after several floods). Boiling and internal erosion have been observed up to 20 to 50 m away from dykes and dams, even though they were only 3 to 6 m high (Fig. 3). Moreover, wide berms are frequently not possible under confined space condition as well as in ecological sensible areas along rivers; therefore drainage trenches are preferred in these circumstances.

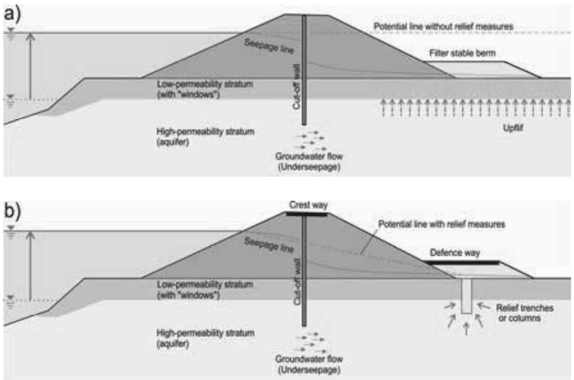

Figure 4. Permanent measures against hydraulic failure caused by underseepage of flood protection dykes: a) Filter stable berm as a counterweight; b) Relief drainage columns or trenches.

However, trenches excavated in very soft soil collapse immediately before geotextiles and fill material can be placed. The installation of trussed retaining panels would be too expensive. These problems could be overcome by developing ‘relief granular columns’, jacketed with a filter geotextile.

Jacketed (coated) stone or gravel columns have been installed in Austria since 1992. At first they were used mainly for drainage purposes, for instance as drainage walls to improve the stability of old flood protection earth dams. This method has significant construction advantages over conventional drainage trenches in loose or soft soil. In critical cases the coated columns are combined with other measures for dam refurbishment. The drainage material (usually clean 4/32 mm, 8/32 mm or 16/32 mm grain) is lowered by vibroflotation, whereby the vibrator is wrapped with a nonwoven geotextile (tied together at the toe of the vibrator).

The tops of relief columns should be covered with coarse drainage material, wrapped in filter geotextiles for longitudinal or transverse drainage. This drainage layer should carry an access road for easy dam defence in the case of severe floods.

Relief columns or trenches are filter stable elements at the landside embankment toe integrated into the dyke profile to reduce the pressure at the base of the low permeable cover layer during the critical flood stages (Fig. 4b). The safety factor against hydraulic failure (erosion or heaving) significantly increases through the controlled pressure relief. The negative effect of this measure is the concentrated groundwater outflow. This can lead under certain hydraulic gradients, soil/subgrade conditions and local topography to an earlier waterlogging of the hinterland.

Figure 4b illustrates also the typical cross-section through a new flood protection dyke after removal of the old one, which had been destroyed by a severe flood. The coated gravel columns (diameter 0.7 m) usually exhibit a spacing between 1.5 and 7.0 m, depending on local factors (geotechnical and ecological parameters, infrastructure, risk potential etc.); spacing is commonly about 4 m. The water-side dam slope is covered by a net for protection against beavers.

Another method to increase the stability against inner erosion is to reduce the hydraulic gradient by raising the water level at the landside in local reservoirs (Fig. 5). This method represents an emergency measure by placing sandbags around the erosion crack and is often used after indication of local hydraulic fracture in the beginning stage.

Figure 5. The giant piping at Tiszhasa/Hungary in 2000 and stabilizing measures (Nagy, 2011): Reduction of hydraulic gradient and lateral support of dyke slope.

4 DESIGN CRITERIA FOR RELIEF DRAINAGES AND ASSESSMENT OF WATTERLOGGING

Until now the design of relief measures (drainage columns or trenches) is based on rather insufficient basic principles, strong simplifications and idealizations. For the quantification of the water outflow from relief columns as well as for a pressure assessment beneath the cover layer only assumptions based on numerical models are in use. These approaches allow indeed comparative calculations of the quantity of seepage through and under the dyke (Fig. 6). But they do not allow an exact differentiation of the waterlogging from flood, precipitation and groundwater of the hinterland. Accordingly, the design of polders and pumping stations can be performed only based on estimated water outflows from the relief drainages.

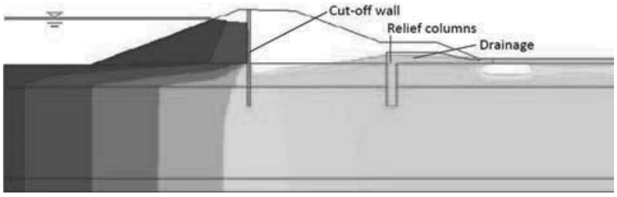

Figure 6. Simplified numerical model of a dyke with relief columns.

Nowadays the assessment of waterlogging is carried out mainly by mapping of water logged areas along the river after floods or heavy rainfalls in combination with digital elevation models (Fig. 7). The results are then combined with numerical simulation studies. Such a long-term monitoring gives some information about the outflow from the relief drainages as well as about the water distribution in the hinterland of the dyke. But it does not allow a detailed design of specific technical measures.

Figure 7. Mapping results for waterlogging with different origin.

Consequently, 1:1 scale model tests on dykes including the subgrade are the best solution to quantify the water outflow from the relief elements during flood stages. Experimental tests performed under laboratory conditions allow a higher degree of reliability than mere numerical simulations. Based on the results from physical modelling an exact calibration of numerical models can be performed.

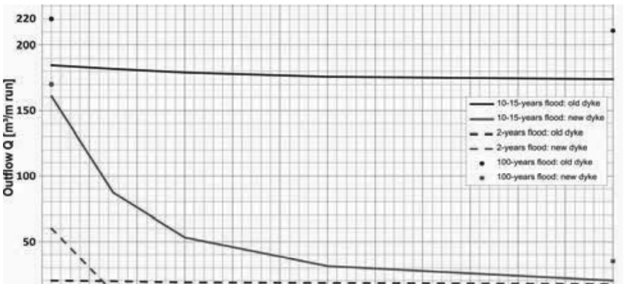

Figure 8. Water outflow Q from the relief drainage versus the distance between riverbed and old or new dyke resp. for different flood events.

In generally, the applicability of results from mere numerical modelling onto natural flow behaviour is strongly limited because of many parameters and boundary conditions. The quantity of water outflow through the relief columns is mainly influenced by subgrade/soil properties, flood wave characteristics, volume of unsaturated aquifer, distance between dyke and riverbed etc. Figure 8 shows the relation between the outflow and distance criterion for an old dyke (insufficient drainage) and the new one (with relief columns).

In the first phase of experimental underseepage studies small-scale (1:10) model tests were carried out at the Vienna University of Technology, Institute of Geotechnics (Fig. 9). The tests results were used for the design of an experimental station for 1:1 scale model tests.

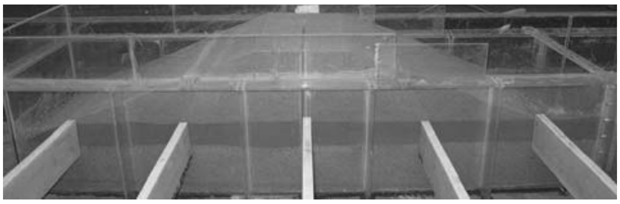

Figure 9. Small-scale model test of a flood protection dyke with simulated subgrade (fine-grained cover layer and permeable aquifer).

5 CONCLUSIONS

In the long-term underspeepage of dykes may lead to erosion processes of the fine-grained soil layers during floods. The hydraulic failure develops mostly very inconspicuously; therefore it is often underestimated in practice. Erosion criteria can be used to describe the critical state for different soil types found during soil investigation. For hydraulic failure prevention landside the dyke filter stable berms or relief columns or trenches have proven.

A technically and economically optimized design of relief measures can be achieved only by combining physical and numerical models. Such a combination takes the specific advantages of both methods. Based on physical model tests a calibration of the numerical model allows detailed parametric studies and makes an application of these results as design criteria generally possible.

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