Assessment of an Embankment Dam Break Warning System Based on Historical Dam Failures

López, Diana[1], Aufleger, Markus[2]

1- Unit of Hydraulic Engineering, University of Innsbruck, Austria
2- Unit of Hydraulic Engineering, University of Innsbruck, Austria

Email: Diana.Lopez@uibk.ac.at

Abstract

Embankment dams offer many outstanding benefits to the society, but like any built structure, dams also pose potential risks for people or property, especially in densely populated areas. If a dam fails, it results in most of the cases in a catastrophic event. The negative consequences could entail not only large loss of property (besides the dam), but also loss of lives.

Principal causes of embankment dam failures are overtopping, internal erosion and problems associated with the foundation. A literature review of historical failure events indicates that there are multiple reasons for dam failure (e.g. a large precipitation, a human mistake, an intentionally act, etc.). Furthermore, most of the cases report that dam crest depressions and other signals were observed at an early failure phase. The conventional monitoring measurements could not give reliable information at the failure begin, in case they were available. Hence, in many cases the failure detection at the dam occurred too late, which reduced the time for executing the mitigation plan downstream.

Embankment dam warning systems are often part of large dams and some selected small dams. The investigation of historical failure events (including the reported warning times) showed that there is the need of an improved warning system detecting failures at an early stage. This paper proposes an embankment dam break warning system, which could be based on the distributed temperature and strain sensing technology (DTSS). The proposed concept offers not only a long term monitoring along the dam crest and the location of a problem, but also the possibility of extending the warning time by early failure detection.

Keywords: warning system, dam failure, dam crest.

1. INTRODUCTION

Embankment dam failures occur due to different processes. According to a conducted study [1] of 75 earth and rockfill embankment dam failures from 1979 to 2009, approximately 48% failed by overtopping, 42% by internal erosion and 9% by foundation problems. The number of embankment dams failed due to hostile actions was extremely low (around 1%) compared to the total number of failures, but they could occur instantaneously. Dams are possible targets in case of wars and terrorist attacks, because of their high damage potential [2].

Insufficient spillway capacities, extreme floods that exceed the design criteria, breaching of an upstream dam, quality construction problems around the spillway or the embedded structures are the most common reasons for embankment dam failures due to overtopping and internal erosion. In addition, foundation problems normally occur due to inadequate material selection and treatment, which finally allows an unwanted water flow. In most cases, these processes cause an important deformation or a local leak at the dam crest, followed by a dam crest overflow.

At the beginning or at least in a relatively early stage of a failure process, a damage or a significant deformation at the dam crest is typically visible. If water starts to leak through an initial breach, the failure progress proceeds quickly and a complete failure of the embankment cannot be prevented at all. The flood wave resulting from the breach depends on the interaction of many parameters (e.g. the velocity, the breach form, water supply and reservoir proportions). Commonly, it exceeds by far the magnitude of a flood event and causes catastrophic damages.

The consequences of an extreme event on dams are estimated by using flood wave methods. They assess the effects of a failure on the individuals living downstream as well as for the local infrastructure and sometimes for the environment. For this purpose, the flood wave models assume a hypothetical failure of a dam or suppose breach formation as a start point for the simulation.

The simulation of the flood wave caused by a dam failure is a complex task. Higher flood velocities and water depths (compared to one from an intense precipitation event), as well as uncertainties due the breach formation progress, sediment transport, topography accuracy, bank stability, roughness choice, model selection or obstacles (e.g. bridge or other structures) make a simulation more difficult [3]. Thus, all these issues affect the results in diverse magnitude.

The flood wave arrival time together with the flood wave propagation (inundated area), water depth and flow velocities are the most relevant results of a simulation and the basis for developing evacuation plans. Typically, the warning time is defined with the time difference between the beginning of the breach development and the occurrence of a critical hydraulic condition (during flood wave propagation) at the downstream areas. Commonly, warning times are in the range of several minutes to a few hours.

2. DAM MONITORING AND WARNING TIME

2.1. EXPERIENCES FROM DAM FAILURES

The structural behavior of an embankment dam is generally monitored depending on the size and type-specific requirements of the structure. The monitoring of large embankment dams often includes the measurement of reservoir level, seepage flow, pore-water pressure, and deformations. Moreover, some of the related measuring systems include in many cases a relatively high number of measuring points, are automatized and provide a remote data transfer. An additional part of the monitoring plan includes frequent visual inspections of the whole dam including abutments, shoulders and the embankment crest. At other structures (e.g. control rooms and appurtenant structures), also facilities such as security cameras or access sensors are often available. As a result, the probability of observing an extreme situation at this type of embankment dams [4] is much higher compared with less monitored embankment dams.

General specifications for small embankments involve less measuring systems, less frequent data recording, and fewer measuring points. Only few structures have automatic data collection and remote data transfer [1]. In addition, seepage monitoring is not always an implicitness. Therefore, a reliable detection of an extreme situation in such cases could be problematic.

Warning times resulting from simulations usually assume an immediate detection of the start of the breaching process at the dam and an instantaneous alarm. To ensure the efficacy of the emergency action plans, real warning times should not fall below them significantly. In this context, the strong dependence between the reliable recognition of a critical condition at the dam (aid monitoring and surveillance equipment) and real warning time is evident.

However, not all embankment dams are monitored with the same frequency and measuring equipment. Often large dams are well monitored. They have generally not only more equipment, but also more measuring points, recurrent data collection, remote data transfer, etc. Hence, most probably an extreme situation could be detected earlier than at small dams. It can therefore be assumed that in general warning times at large embankment dams are longer.

19 documented embankment dam failures at the USA [5] shows that real warning times were extremely short and in most of the cases (84%) an alarm activation was just given after the complete failure (warning time = 0). According to the definition of the International Commission on Large Dams (ICOLD) for dam classification, 68% of affected embankment dams were small and in all of them the warning time was zero. Furthermore, warning times longer than 1 hour were only available at 50% of the large one.

2.2. SITUATIONAL WARNING TIME

The warning time is considered situational due to the close relationship with the monitoring plan, the detection of a problem at the embankment dam and the alarm activation downstream. This definition will be reviewed in this work using three potential situations shown in Figure 1. On top a well-monitored embankment dam (i.e. continuous seepage measurement with remote data transfer), in the middle one equipped with fewer elements (only reservoir level measuring with remote data transfer) and at the bottom the worst case, an embankment dam with no monitoring at all, are displayed.

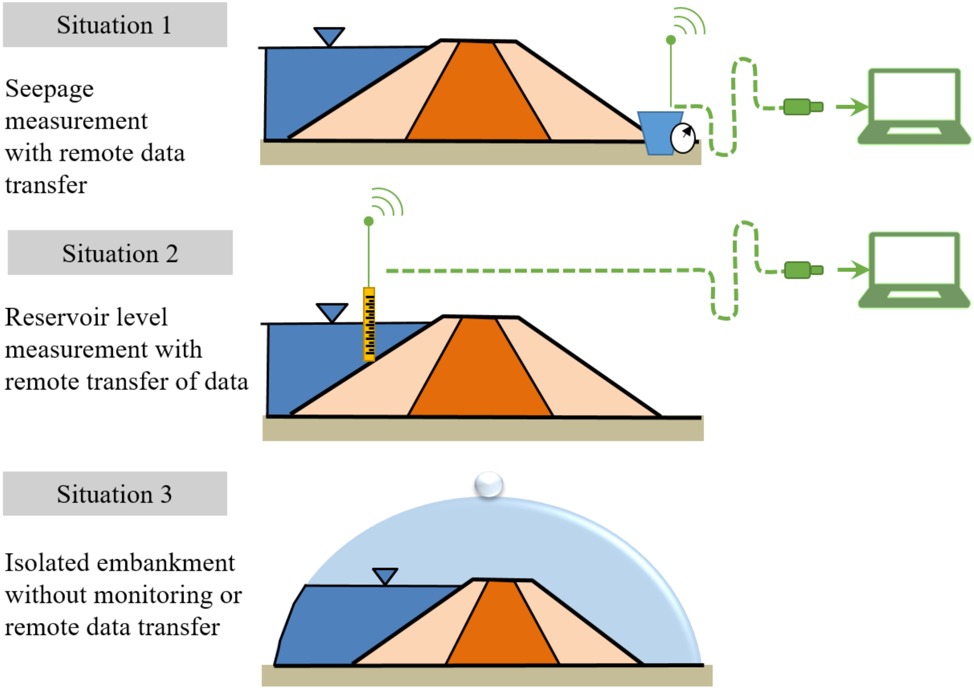

Figure 1: Embankment dam with three different monitoring plans

Figure 2 shows the cross-section from an embankment dam along the flood path to a residential area downstream. Furthermore, two gauges at different locations, one at the embankment dam and another at the residential area downstream, are marked in blue and green [4].

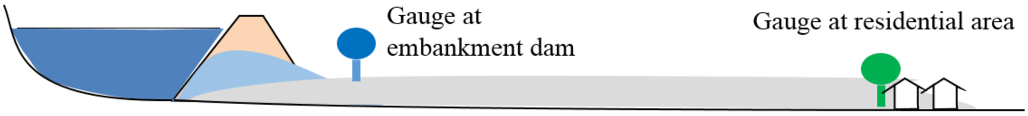

Figure 2: Cross-section with gauges and flood waves [4]

Figure 3 shows the situational warning times, the failure progress and the hydrographs at the gauging stations defined in Figure 2 for the three monitoring situations defined at Figure 1. Here a typical internal erosion process is shown also starting with the formation of an erosion tube that then expands until it collapses and the embankment dam breaches.

The first monitoring situation leads to a fast observation of seepage flow rise. Consequently, the occurrence of internal erosion is detected at a very early stage and the warning time is relatively long.

The second situation represents an embankment dam with a water level monitoring with remote data transfer. It is supposed, that there are alarm values activated that allow the identification of unusual fast drops of the reservoir water level. In this case, the internal erosion detection happens at a later time (after the breach initiation and the start of an uncontrolled outflow from the reservoir) and the warning time is shorter compared to situation 1. The efficiency of an evacuation plan is reduced significantly compared with the first monitoring situation.

The third situation represents the worst case without any remote date transfer. The alarm will be activated after the whole breach, when the flood wave hits the residential area. Thus, the warning time at the residential area is missing, the mitigation plan could not be implemented and the negative repercussions downstream are most catastrophic than by the other situations.

The above considerations do assume that the development of the internal erosion process could not be detected within the scope of the regular dam surveillance procedures (e.g. visual inspection). Thus, in a certain way this comparison has to be considered as a schematic approach in order to present the fundamental relationships in a simple way.

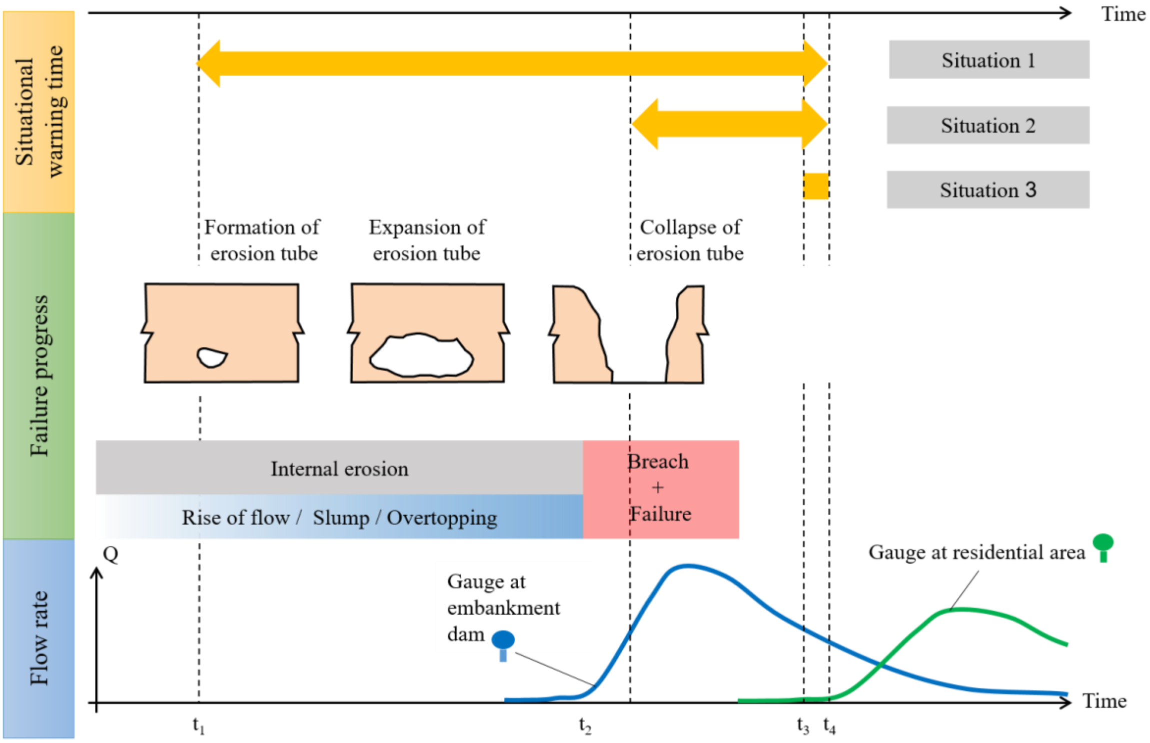

Figure 3: Cross-section with gauges and flood waves

2.3. CURRENT WARNING SYSTEM

There are a number of different systems for warning of an imminent dam failure. These include video surveillance (e.g. closed-circuit television), strong motion digital accelerometer and geotechnical instrumentation with automated data acquisition [6].

Methods such as close-circuit television (CCTV) can be particularly useful where defects below water level or in inaccessible areas are suspected and an inspection is required without lowering the water levels [7]. However, these systems require site personnel to point out an anomaly.

Strong motion digital accelerometers are special required in earthquakes susceptible areas. They range from seismic alarm devices to digital accelerographs installed in the foundation. The high installation and maintaining costs make this system no reachable for all structures. Furthermore, some experts consider it only in some cases meaningful, because of the low probability of obtaining significant data. [8].

3. THE DAM CREST IN EXTREME SITUATIONS AND THE PROPOSED WARNING SYSTEM

The dam crest is a suitable indicator of the dam condition in extreme events. Particularly high water levels in impoundment (e.g. due to unexpected extreme inflow or severe problems at appurtenant structures) cause higher shear stresses which bring erosion forward. The following overtopping performance depends essentially on the embankment fill type [9]. Even after a shorter or longer time period, along with the formation of an initial breach, deformations may be registered in the dam crest.

A similar performance could be observed in cases of embankment dam failures due to internal erosion. Failures due to this mechanism involve a long process and their detection is normally very difficult. For instance, after the formation of an erosion tube, the process of the following expansion of the tube could conclude in diverse scenarios [10]. The most frequent scenario covers deformations and/or sinkholes which could be observed during the breach formation and before the overtopping of the embankment. The occurrence of a cavity which crosses the body of the embankment dam with a subsequent reservoir emptying is a less frequent scenario.

According to the previously mentioned embankment failure study, in all failure cases due overtopping and in around 84% of the failures due internal erosion, a clear change or a relevant deformation of the dam crest was evident in an early phase of the failure development -usually at the start or before of the breach formation-. Therefore, the observation of these deformations could not only extend the warning time in several cases but also give further information about the breach development (e.g. the location and the approximate size of the anomalies respectively the significant deformations).

In conclusion, as soon as a noticeable damage at the embankment crest is identified, a major risk for the dam structure could be assumed. So, a reliable and early recognition of a problem by means of an embankment dam break warning system contributes to improve the management of the remaining risk and consequently to enhance the safety of the people living downstream.

Currently, it seems that there is no warning system for monitoring the entire embankment crest internally and permanently under operation. Therefore, this work proposes a cable-based warning system installed at the embankment dam crest.

Distributed fibre optic measurements along cables offer the option of measuring temperature and strain as a continuous profile along a single optical fibre. In other words, the distributed temperature and strain sensing (DTSS) permits monitoring of deformations lengthways the entire fibre optic cable. Compared to conventional sensing techniques, this distinctive feature made this technology interesting for monitoring of large structures such as dams, tunnels or bridges. Indeed, a remarkable advantage of this sensing system in internal parts of dams is the detection and localization of differential deformations where a single point, geodetic or visual monitoring methods are not feasible [11]. The use of cable - based systems is well known through the successful application in civil engineering [12], [11], [13], [14], [15], [16]. However, for the purpose to use this technology as an operative and reliable dam failure warning system, several adjustments are necessary and discussed in the following.

The monitoring of the dam crest integrity as an indicator of the probable condition of the embankment dam using a cable – based system for early detection of a dam failure could contribute to an increasing of the safety level of an embankment dam in extreme situations. Basically, the warning system consists of a DTSS sensor cable that is installed lengthwise in the embankment crest within the dam structure and of a measuring system which is located at a convenient and safe position [4] (see Figure 4). For this purpose, a high accuracy of the temperature and strain sensing system is not required. However, it has to be able to confirm the dam integrity through it permanent functioning (i.e. by means of continuously recurrent measurements). In addition, in the case of a significant structural change at any point of the embankment crest, the warning system has to provide an immediate detection of the position and depending on the possibility, the approximated magnitude. Then, the collected information has to be automatically and directly sent to the responsible person (e.g. operator or safety responsible person). Other requirements associated with the system and its effectiveness in several structures are great robustness, low maintenance efforts and reasonable installation costs. The idea is to implement this safety measure in newly built embankments (large and small embankment dams), but also in existing structures with a reasonable effort.

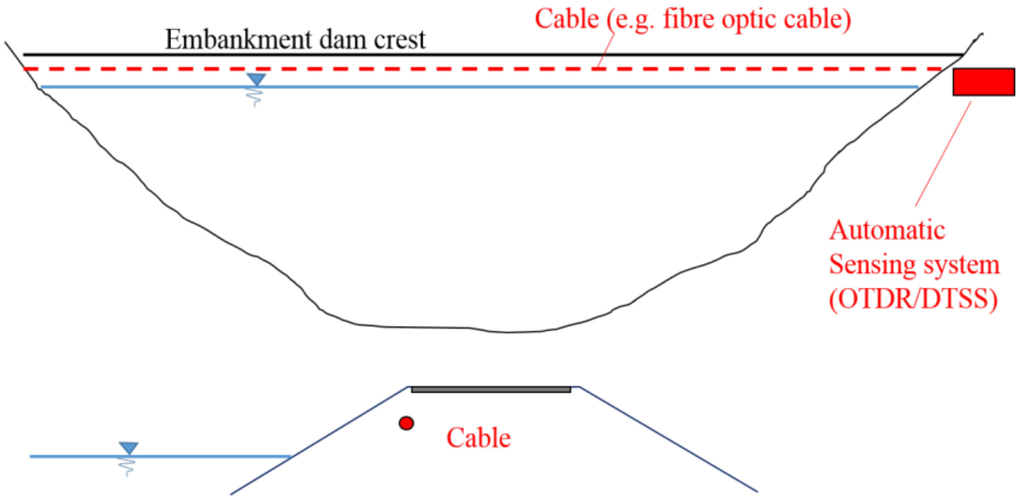

Figure 4: Cable based warning system [4]

4. CONCLUSIONS

Failure mechanism such as overtopping and internal erosion are the cause of approximately 90% of the registered embankment dam failure cases. The residual 10% of failures are attributed to problems in the foundation and sabotage actions. Despite, the continuous improvement of the construction of embankment dams, a remaining risk of a dam failure is present. The development of dam break warning systems, which handle these outstanding threats is recommended. Furthermore, the systems should be applicable and financially reachable for small and large embankment dam projects.

Based on the analysis of the historical dam failure cases, the embankment crest could be considered as a consistent indicator of the dam structural behavior – especially during extreme situations. A suitable cable based sensing system located longitudinal in the embankment dam crest in a shallow installation depth could contribute to enhancing the dam safety (people, infrastructure and environment).

5. OUTLOOK

Although cable - based dam warning systems installed at the dam crest could provide important data about the breach formation and its development, essential issues such as the system efficacy, the scope of application, and the detailed description of the installation require further research.

Physical models and numerical simulations are suitable for studying the possible scenarios of a dam failure. A combination of both simulation methods could contribute in different ways to a further development of the cable based warning system. A physical model can provide significant information about the installation (system set-up) and the efficiency in diverse materials. In addition, the numerical simulation could investigate dam failure scenarios, and therefore, improve the data about the scope of application.

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