The Issue of Dikes and Embankment Dams’ Safety

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1. INTRODUCTION

The safety of embankment hydraulic structures, such as large or small embankment dams, canal embankments and flood protection levees, are still a major concern on every continent. Every year, there are several breaches of large embankment dams and hundreds of breaches of levees worldwide. This paper presents the three potential failure modes of embankment hydraulic structures and shows which ones are the most dangerous. Then it presents how embankment hydraulic structures are designed to avoid a failure. Among their defence barriers, one is particularly important during their entire life: this is the surveillance, which includes both visual inspections and monitoring. In its last part, this paper discusses the limitations of conventional surveillance to detect early one of the main causes of breaches, which is internal erosion.

2. POTENTIAL FAILURE MODES OF EMBANKMENT DAMS AND DIKES

Hydraulic embankment structures are subject to three potential causes of breach:
- Shearing, which includes all breaches because of instability and particularly instability caused by major sliding of the downstream slope or the upstream slope under static loading, or instability caused by major sliding under seismic stress, or liquefaction (cf. Fig. 1);
- External erosion, which includes erosion due to overtopping and scouring of the upstream slope toe (cf. Fig. 2);
- Internal erosion, which may start because of conduit erosion, regressive erosion, contact erosion or suffusion (Fig. 3).

![Fig. 1: Breaching by shearing](image1)

![Fig. 2: Breaching by external erosion (overtopping)](image2)
The four processes of internal erosion initiation are:
- Conduit erosion: soil particles are removed from the surface of the conduit under the action of the flow (cf. Fig. 4);
- Regressive erosion: soil particles are removed under a cohesive surface or at the flow exit. Then erosion progresses upward (cf. Fig. 5);
- Contact erosion: fine soil particles are removed along an interface between a coarse material layer and a fine material layer, under the action of the flow crossing the coarse material layer (cf. Fig. 6);
- Suffusion: fine soil particles are transported by the flow in the voids between the matrix of coarse materials (Fig. 7).

According to Foster and Fell’s statistical study of breaches in large embankment dams:
- shearing represents 6% of breaches;
- internal erosion represents 46% of breaches;
- external erosion represents 48% of breaches.

There are no equivalent statistics for small embankment dams or canals and flood protection levees, but it is accepted that similar proportions are valid for these structures.

Even today, several breaches of large embankment dams occur every year. Unfortunately,
there is no international database for breaches of dams and levees, but there are several hundred breaches of large embankment dams, without data from China, or data on breaches of flood protection levees, which are still not inventoried and probably total thousands. In 2013, amongst others, there was the breach of Lianfeng dam in northern China on February 2\textsuperscript{nd} and the Oaky River dam breach in Australia on February 22\textsuperscript{nd}.

If the Oaky River dam breach was fairly well documented and clearly caused by overtopping, very little information has been diffused to date on the breach of Lianfeng dam. It would appear, nonetheless, to be due to internal erosion that developed around a cross structure (spillway, bottom outlet?).

In France, the last major floods were the ones that occurred on the Rhone in 2002 and 2003 (around the 100 year return period). These floods caused considerable damage in the region of Arles, estimated at about 1 billion euros both years. The damage was mainly caused by breaches in several levees, due to internal erosion.

The study of breaches in embankment hydraulic structures due to internal erosion shows that 95% of the breaches appear when the upstream reservoir reached its highest level. The causes are the presence of cracks for the dams (desiccation, shearing of the core, differential settling or earthquake) and holes made by burrowing animals or tree roots for the levees. Since breaches due to overtopping are also caused by extreme hydraulic loading levels, we note that the large majority of breaches in embankment hydraulic structures occur in flood situations.
3. HOW ARE EMBANKMENT DAMS AND DIKES PROTECTED AGAINST THEIR POTENTIAL FAILURE MODES: THE DEFENSE BARRIERS

Embankment hydraulic structures have to be designed with passive defense barriers, which are structural components of the dam or the levee and one active defense barrier, which is the surveillance. During all its life, the dam or levee must have at least two to three satisfactory defense barriers, including every time the surveillance.

3.1 PASSIVE DEFENSE BARRIERS

Embankment hydraulic structures are designed with 6 passive defense barriers. Each one is a structural component of the embankment. These passive defense barriers include:
- Sealing;
- Filtration;
- Drainage;
- Protection of upstream and downstream faces;
- Stability of upstream and downstream fills;
- Evacuation.

3.2 THE ACTIVE DEFENCE BARRIER: THE SURVEILLANCE

Surveillance includes both visual inspections, monitoring and their interpretation. Surveillance must be performed all along the structure’s life. Its objective is to check if the safety margins of the dam or levee which were defined at the design stage are still valid through time. Two time scales of surveillance can be defined:
- A long-term surveillance, which objective is to verify if the mechanical and the hydraulic behaviours of the dam or levee evolve satisfactorily through time;
- A short-term surveillance, which objective is to check if the safety margins of the dam or levee are still satisfactory during severe load events, such as floods or earthquakes.

4. THE SURVEILLANCE: THE MAIN ISSUE OF EMBANKMENT DAMS AND DIKES’ SAFETY

Surveillance, which includes visual inspections and monitoring, constitutes one of the main methods for preventing these structures from breaching because of overtopping or internal erosion. However, the surveillance implemented to date on these structures presents two main weaknesses: 1) the monitoring measurements are unable to detect internal erosion early, which causes almost half of the breaches, and 2) the owners do not generally have a system that allows real time monitoring of the structure during floods, although it is precisely during extreme hydraulic loading (extreme flooding) that the structures have the lowest safety margins, particularly as regards the risk of a breach due to internal erosion. The lack of an early alert to the development of pathologies that can lead to a breach in the structure considerably reduces the chances of preserving the structure’s integrity through emergency reinforcement and increases the risk of material and human loss.
Surveillance includes visual inspections and monitoring. In France, surveillance of small embankment dams and canals is generally based on the provisions listed in Table 1 below.

<table>
<thead>
<tr>
<th></th>
<th>Regular surveillance</th>
<th>Surveillance in flood</th>
<th>Post-earthquake surveillance</th>
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<tbody>
<tr>
<td><strong>Visual inspections</strong></td>
<td>1 - 2 inspections per month</td>
<td>Inspection in flood, but staff limited and do not work at night</td>
<td>Inspection following an alert, depending on magnitude and distance from the epicentre.</td>
</tr>
<tr>
<td><strong>Monitoring</strong></td>
<td>Hydraulic behaviour based on piezometric measurements and/or drainage flow measurements. No remote measurement. Mechanical behaviour rarely monitored (possibly altimetry measurements).</td>
<td>No monitoring during the flood (no teams available for this type of task and no telemeasuring).</td>
<td>Monitoring tour following an alert depending on magnitude and distance from the epicentre.</td>
</tr>
</tbody>
</table>

Table 1: Small embankment dams and canals’ surveillance provisions applied to date in France

In France, surveillance of flood protection levees, when it exists, is generally based on the provisions listed in Table 2 below.

<table>
<thead>
<tr>
<th></th>
<th>Regular surveillance</th>
<th>Surveillance in flood</th>
<th>Post-earthquake surveillance</th>
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<tbody>
<tr>
<td><strong>Visual inspections</strong></td>
<td>Inspection 1 to several times per year</td>
<td>Inspection in flood, but staff limited and do not work at night</td>
<td>No visual inspection following an earthquake.</td>
</tr>
<tr>
<td><strong>Monitoring</strong></td>
<td>Generally, no monitoring in regular surveillance conditions</td>
<td>Hydraulic behaviour based on manual measurements of the upstream water level and rarely supplemented with piezometric measurements (also manual). No monitoring at night in flood.</td>
<td>No post-earthquake monitoring.</td>
</tr>
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Table 2: Surveillance provisions for flood protection levees applied to date in France

These provisions show that the hydraulic behaviour of large linear embankment structures and small embankment dams is essentially based on piezometric measurements, drainage flow measurements and, in the case of flood protection levees, manual measurements of the upstream water level.

The piezometric and drainage flow measurements, which are only used to monitor the long-term hydraulic behaviour of structures, are important measurements but often fail to detect internal erosion early.

On numerous EDF canal structures, subject to slow kinetic internal erosion pathologies such as suffusion or contact erosion, seepages linked to solid transport were not detected by
piezometric measurements taken just a few metres away. Indeed, a localised seepage in the embankment, if it is not very large, never causes a significant increase in pore pressure beyond a few metres around it.

The drainage flow measurements provide important information since they collect seepage over hundreds of metres. However, in practise, if the flows measured are located in the toe of the downstream slope in a drainage ditch, they also collect inflow from the water table, or even inflow from surface tributaries connected to the drainage ditch. The drainage flow measurements therefore integrate several sources of flows and it is often difficult to interpret them for the required information, i.e. the flows of seepage through the structure and/or its foundation.

The conventional monitoring measurements used to date to monitor the hydraulic behaviour of large linear hydraulic structures are therefore not well adapted to the early detection of internal erosion.

An examination of the surveillance provisions applied to date in France for large linear embankment structures and small embankment dams therefore highlights that, during the most dangerous load situations, i.e. extreme floods, which lead to the lowest safety margins of structures with regard to potential causes of breaches, the active defence barrier constituted by surveillance is largely insufficient due to globally inoperative monitoring. This lack is mainly characterised by:
- a lack of measurements of the physical parameters that are the most relevant for the early detection of the appearance of seepages in a structure that can lead to internal erosion;
- a lack of an adapted human organisation to take monitoring measurements and analyse them in real time during floods.

5. CONCLUSION

The main failure modes of small embankment dams and levees are internal erosion and external erosion by overtopping. Several hundreds of such failures occur every year worldwide. One of the main defence barriers against these failure modes is surveillance, which includes both visual inspections and monitoring. Many small embankment dams and levees present a lack of surveillance and sometimes no surveillance at all. When surveillance is performed, conventional monitoring technologies and human organizations are unable to detect early internal erosion or external erosion by overtopping during severe load conditions (severe floods).

Dam owners have to improve their surveillance in two directions:
- providing human organizations able to perform real time surveillance during floods (24h/24, 7 days a week);
- installing monitoring equipments enabling remote surveillance and also able to detect early internal erosion and extremely high levels of water of the upstream face of the structure.

The means devoted to surveillance must be adapted to the safety issues and risks (number of people living in areas potentially inundated if a breach occurred).