Detection of Internal Erosion Using Seismic Techniques

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ABSTRACT

Internal erosion is one of the major causes of failures of earth embankment dams. Its complexity lies in understanding the stages that would lead to failure (i.e. initiation, continuation, progression and breach). Visual signs on the structure usually happen in the advanced stages (i.e. progression) and are directly followed by the breach. Therefore, it is of utmost importance to detect the behavior of the structure during the initial phases of internal erosion in order to prevent catastrophes from failure. The aim of this paper is to detect the different phases of internal erosion using geophysical techniques. For this purpose, a small scale laboratory setup was mounted in order to visualize internal erosion in a controlled environment. Vertical geophones were placed to monitor the seismic response throughout the different stages. The analyses of the seismic data consisted of obtaining the time series throughout the experiment and highlighting the major events. The spectrogram identified the concentrated leak type of internal erosion through the frequency range signature of the events when soil particles rearrange and are being washed away due to the hydraulic forces.

INTRODUCTION

Earth dams have been widely used for water storage for the purpose of irrigation. They are built with materials such as sand, clay and gravels (U.S. Bureau of Reclamation, 2015). Many of the earth dams worldwide especially in the United States are old structures that require close monitoring. Internal erosion is caused when soil particles exit the foundation or the body of the earth dam downstream (ICOLD, 2017). This phenomenon is initiated when the hydraulic forces are higher than the ability of the materials to withstand them; when one of these mechanisms takes place: (1) Concentrated leak erosion which occurs in cracks and openings in the structure and often happens in plastic soils; (2) backward erosion and piping happens in non-plastic soils when an erosion pipe initiates at the downstream toe and progresses upstream ('backwards') all the way to the upstream toe in the reservoir; (3) contact erosion takes place at the interface of fine and coarse grained soils; and (4) suffusion when the fine particles are driven through the coarse soil matrix in gap graded soils (ICOLD, 2017).

Statistics show that 46% of failures in earthen dams are due internal erosion (Xu et al., 2013; Foster et al., 2000; Xu and Zhang, 2009; and Zhang et al., 2009). Internal erosion takes place mainly in concentrated leak erosion, suffusion and contact erosion (Xu et al., 2013). In concentrated leak erosion, the forces imposed by water flowing through cracks and openings initiates the detachment of soil particles leading to erosion of the walls of the cracks and openings forming a channel or an erosion pipe between the upstream and downstream sides of earth embankments which can lead to breach (Benahmed and Bonelli, 2012).

Detection of anomalies in the body of earth dams have focused previously uniquely on visual inspections which is not enough to determine the early stages of internal erosion that would prevent the collapse (Belcher et al., 2015). Therefore, extensive work has been done in this area to monitor the structure and define the anomalies. Installation of sensors to detect temperature, pore pressures and relative inclination, among others, are installed inside the dams to detect variations (Pyayt et al., 2011). In this paper, the work focuses on detecting major events that would lead to breach using geophysical techniques; mainly seismic. Previous studies have been conducted with the purpose of identifying events that happen during internal erosion using this technique (Fisher et al., 2016; Planes et al., 2016; Maalouf et al., 2019; Gerrit et al., 2017 and Hu et al., 2018). The seismic signals processed showed that the events happening inside the body of the structure are being captured using geophones installed on the surface of the dam in order to monitor the water flow and particle movement. For this purpose, a laboratory setup was built to simulate the concentrated leak erosion. Results show that water flowing through the crack in the soil structure was detected as well as the soil failures due to the forces imposed by the flowing water.

METHODOLOGY

The laboratory setup consists of a concrete beam (L = 1.50 m, H = 0.50 m and W = 0.18 m) with a 10-cm diameter hole in the middle where the soil mixture is placed. The purpose of using a concrete beam is to ensure that the events detected in the experiment are only due to the seepage of water in the weak soil sample zone. The beam is connected to a tank to control the hydraulic head. Figure 1 shows the setup of the experiment. The concrete beam is installed on neoprene pads in order to minimize the seismic noise caused by the laboratory activities, machinery and students movements.

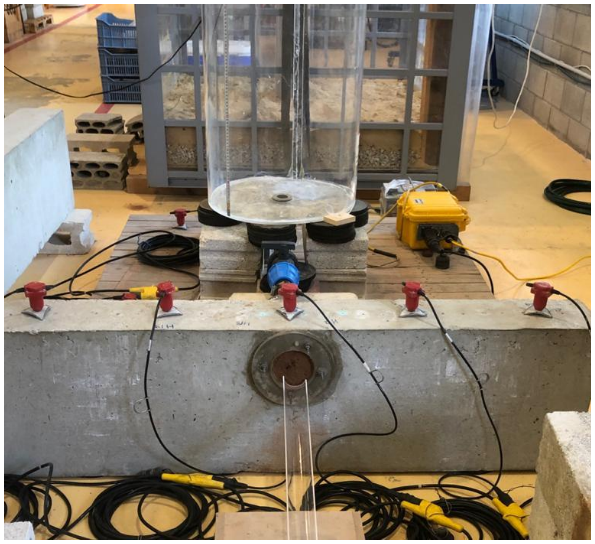

Figure 1 - Laboratory setup of the seepage device - the concrete beam and the weak zone. The soil sample is put inside the pipe and then submitted to a given hydraulic head. Geophones are placed on top of the concrete beam (red cones) to record the seismic ambient noise and the seismic activity linked to the water/soil interactions.

In this test, a mixture of 50% sand (γ_d = 14.2 kN/m^3) and 50% clay (properties summarized in Table 1) was prepared. The sample was mixed at hygroscopic moisture content and then water was added to reach a moisture content of approximately 10.9% leading to dry unit weight γ_d = 15.4 kN/m^3. For the simulation of concentrated leak erosion, a hole of 8 mm was drilled in the center of the soil as shown in Figure 2. This setup is similar to the Hole Erosion Test that was developed by Wan and Fell (2002, 2004a, 2004b and 2008) and Benahmed and Bonelli (2012). Details of the test process and examples of results are given in ICOLD (2016).

In total, 8 vertical geophones of 4.5 Hz normal frequency were used to monitor the experiment. Geophone 1 was placed on top of the water tank, geophone 2 on the wood plank, geophone 3 on the floor next to the concrete beam and geophones 4, 5, 6, 7 and 8 are mounted on the top of the concrete beam at a spacing of 30 cm to monitor changes in the beam. Geophone 6 is located on top of the weak soil zone (Figure 1). The sampling frequency is of 500 Hz.

A 1-minute period was recorded without any water movement in order to monitor the ambient seismic noise in the laboratory especially the events due to students working. Then the upstream valve is opened to allow water seepage through the weak zone.

The data acquired are loaded into Matlab for further analysis. The time series is compared between geophone 3 placed on the floor next to the setup and geophone 6 corresponding to the sensor placed on top of the weak zone. Detection of a series of events and failure are observed on the time series for both experiments. The spectrogram representing the frequency signature of the data is then presented. This analysis helps in the identification of the frequency range where the events take place and which are more energetical.

Table 1 - Clay Properties

Cohesion - c' (kPa)	38
Angle of friction - ϕ′ (º)	27
Dry Density - γ_d (kN/m^3)	18.9
Permeability - k (m/day)	0.035×10^{-3}
Plastic Limit(%)	22
Liquid Limit (%)	47
Optimum Moisture Content (%)	21.4

Figure 2 – Weak zone for the concentrated leak testing showing the 8 mm hole in the middle of the sand-clay mixture

PRESENTATION AND DISCUSSION OF RESULTS

The time series corresponding to geophone 6 is presented in Figure 3. At time t_1 = 3 mins the valve is opened to permit water seepage into the sample. Small events are detected between t_1 and t_2 = 13 mins where small particles are being washed away from the hole as seen in Figure 4 – showing beakers containing soil particles detached from the weak soil sample zone and transported downstream at different time intervals during water flow. For t_3 between 17 and 19 mins, collapse (lump of soil falling) of soil is observed at the downstream end of the weak zone. At t_4 = 19 mins, the entire weak zone failed resulting in a big event of high amplitude highlighted in Figure 3.

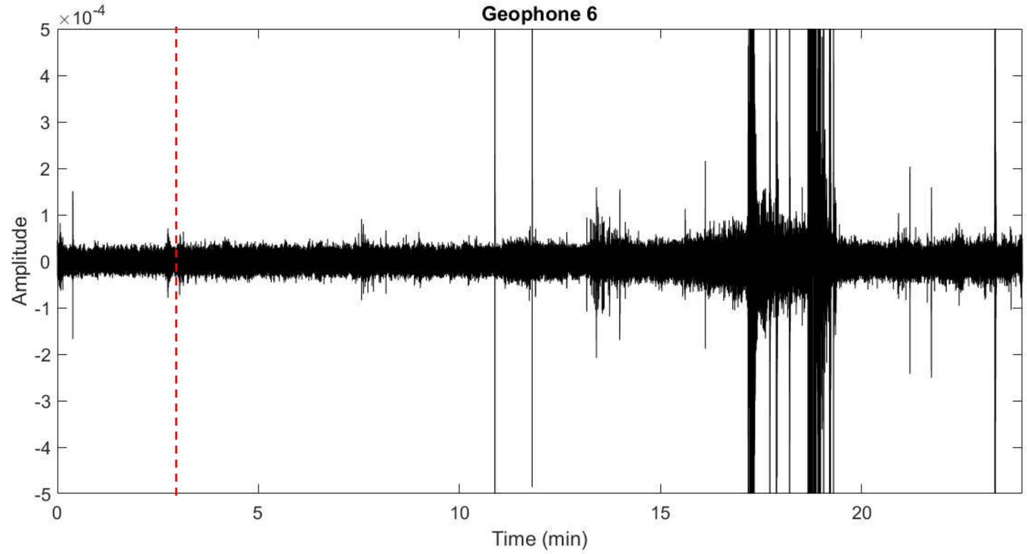

Figure 3 - Time series of geophone 6 on top of the weak zone identifying small events happening in the weak zone due to the collapse of soil and soil particles movement

Figure 4 - Water samples collected during water seepage in the hole. Beaker 1 corresponds to the time when samples were first witnessed downstream (6 mins), beaker 2 is during the first collapse (13 mins) downstream and beaker 3 corresponds to the time before the failure of the weak zone (15 mins)

Figure 5 shows the spectrograms of (a) geophone 3 located on the floor and (b) geophone 6 located on top of the weak zone. The high energy signal at 50 Hz corresponds to the electrical power in Lebanon. High energy events observed between 25 and 50 Hz and 75 and 100 Hz correspond to the water flowing in the weak soil sample zone and they appear immediately after the opening of the valve at t_1 = 3 mins. Those events do not appear anywhere in Figure 5 (a) on Geophone 3 which proves that these events are due to the mechanical changes happening strictly in the weak zone and are not due to laboratory activities or machinery. Between 17 mins and 19 mins the collapse of the entire weak zone is observed downstream and moving upstream. The red squares highlighted in Figure 5 (b) indicate a drop in the frequency in the frequency ranges of 60 to 30 Hz and 225 to 175 Hz. This decrease starts at time t_5 = 6 mins when the soil particles are observed exiting the hole (shown in Figure 4 beaker 1). This effect could be due to the enlargement by erosion of the walls of the hole (from 8 mm to 9 mm).

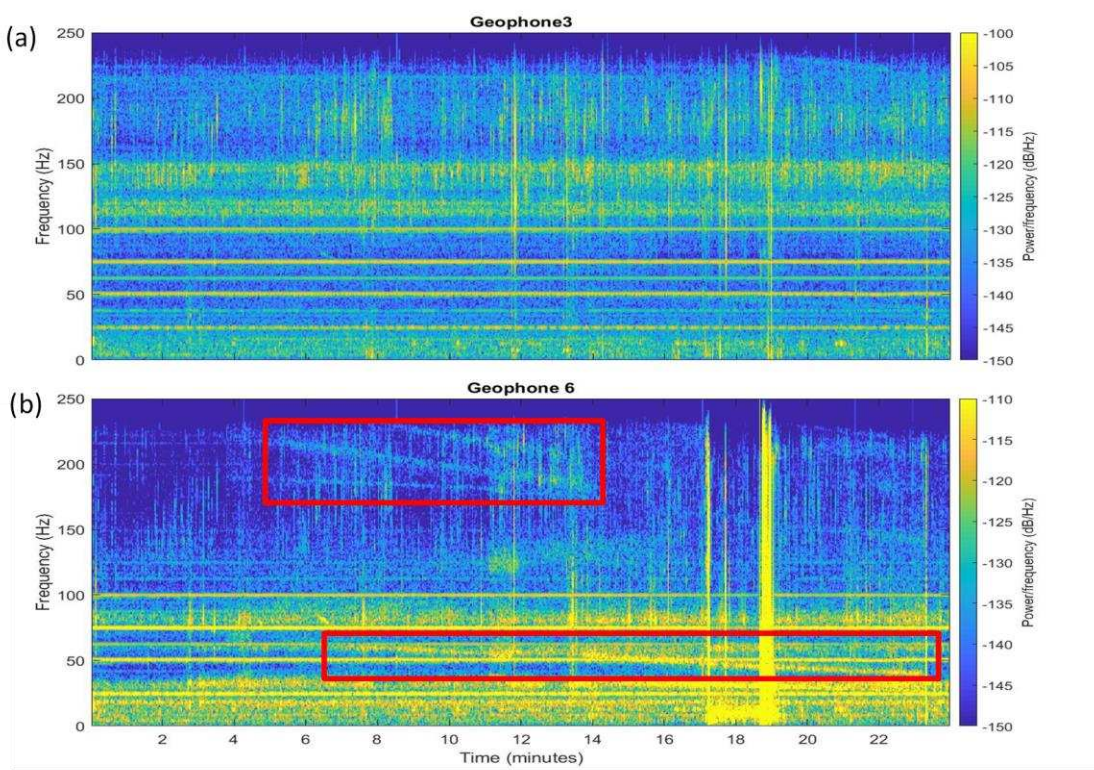

Figure 5 - Spectrograms for (a) Geophone 3 located on the floor next to the concrete beam and (b) geophone 6 located on top of the weak zone. It is evident that both spectrograms are not identical and that geophone 6 shows multiple events that are caused by the soil particles rearrangement and movement in the weak zone

This experiment shows in Figure 6 how concentrated leak erosion commences at the downstream end and progresses upstream causing a complete collapse failure of the weak soil zone at the end of the experiment.

Enlargement by erosion of the walls of the hole can be seen in Figure 6(a) and 6(b), but in 6(b) the lower part of the sample near the exit has collapsed. In 6(c) the upper part of sample has also collapsed, disrupting flow through the hole, and possibly causing collapse and closure of the hole as the now very wet sample collapsed. Experience with the Hole Erosion Test shows that sandy plastic soils usually collapse on saturation, making the test best suited to non-sandy plastic soils (ICOLD, 2016).

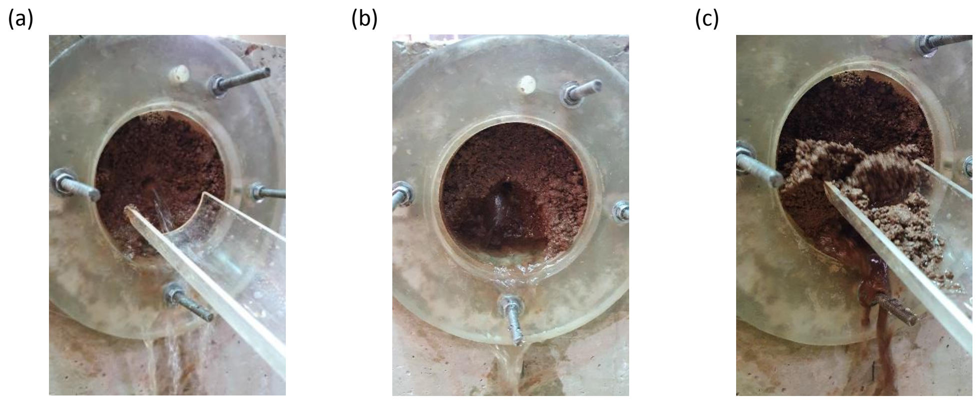

Figure 6 - Photographs taken throughout the experiment. (a) corresponds to the beginning of the experiment during water seepage; (b) corresponds to the first collapse at 7 mins and (c) corresponds to the collapse happening downstream at 13 mins

CONCLUSIONS

This experiment simulates concentrated leak erosion through a controlled environment. Geophones are placed on the top of the concrete beam and at places away from the experiment to identify events coming from the weak zone. The data acquired throughout flow detected the presence of events at different frequency ranges identifying the multiple stages in internal erosion such as seepage, water movements, collapse and breach. The drop in the signal frequency when water was flowing could be due to the fact that the hole diameter was enlarging. The hydraulic forces from the water flow along the hole became higher than what the materials could withstand thus causing instability, initially at the downstream end and progressing upstream. Thus, the collapse reached the upstream end of the sample and the entire specimen failed. It is difficult to say with certainty that erosion was the only cause of the collapse because wetting of sandy plastic soil samples often causes them to collapse in Hole Erosion Tests. Multiple similar experiments should be conducted at different sand to clay ratios in order to examine the potential of seismic techniques to identify the onset of concentrated leak erosion in greater detail. Continuous measurements of turbidity would make it possible to confirm the quantities and sizes of the eroded soil particles.

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