Using accelerometers in landslide flume experiments to detect pre-failure signals

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Abstract

Early Warning Systems (EWS) are non-structural measures for disaster prevention: their main objective is to alert the population with enough time to take actions to prevent losses and damages, by detecting, monitoring, analyzing and forecasting hazards and possible consequences. The use of sensor nodes for monitoring landslide prone hillsides is gradually increasing and showing promising results. This paper presents the first results of an ongoing research to test the use of accelerometers as sensor nodes for monitoring landslides in a joint effort of Campinas State University and the Institute for Technological Research in São Paulo State, Brazil. Before using those devices in real cases it is necessary to validate their use in laboratory conditions. This research intends to test the capacity of the accelerometers to identify signals that may foresee the occurrence of landslides in laboratory conditions. For that purpose, an experimental apparatus, called "tilting flume", was built to simulate landslides with various soils in different humidity and compaction conditions. So far, landslide simulations have been performed with a poorly graded sandy soil, in dry conditions, at maximum soil density and by tilting the box till failure. The soil was reinforced with a geosynthetic placed at its half-height and the failure occurred along the soil-geosynthetic interface. Two types of accelerometers were used, which differ from each other in frequency acquisition and amplitude features. This paper presents the results of the first two experiments and knowledge gained with them. Raw data collected in these experiments show that pre-failure signals can be measured. To identify these signals in this kind of soil and under those testing conditions it is mandatory to work with high frequency acquisition ratios, since pre-failure signals can occur relatively close to the moment of failure. Next research steps include signal processing and performing experiments in wet conditions, in order to simulate more realistic rainfall triggered landslides.

1 INTRODUCTION

Landslide disasters have become increasingly frequent due to the spread of cities in areas prone to the occurrence of this type of geological hazard. Early Warning Systems (EWS) are a non-structural measure for disaster prevention: their main objective is to alert the population with enough time to take actions to prevent losses and damages. Hence, EWS are alternatives to prevent losses and damages when implementing stabilizing measures is not feasible due to higher financial cost and environmental impacts (Corominas et al, 2015).

According to Askarinejad et al. (2018), for a successful disaster mitigation it is necessary to understand properly triggering mechanisms and interactions between geomechanical, hydrological and hydrogeological features of the slope and also to have an efficient evacuation strategy.

Since precursors of failure in slopes might happen relatively close to the final stages of the rupture, it is necessary to use high-resolution monitoring techniques that minimize the need of human in situ measurements.

The use of sensor nodes, through the implementation of Wireless Sensor Networks (WSN), for monitoring environmental disasters is gradually increasing and showing promising results. The main advantages of using sensor nodes are: real-time monitoring, high resolution, low cost and high data processing and storage capacities. The use of these sensors can provide information about the potential triggering of landslides, and show signs that precede and characterize the movement.

An ongoing research is studying the use of low cost sensors – accelerometers and Frequency Domain Reflectometry (FDR) humidity sensors – as sensor nodes for monitoring landslides in a joint effort of Campinas State University and the Institute for Technological Research, in Brazil. That research intends to test in laboratory conditions the capacity of low cost sensors - accelerometers and FDR humidity sensors - to identify signals that may foresee the occurrence of landslides.

The use of accelerometers as sensors for measuring velocities in landslides is a new and promising geotechnical monitoring technique, as presented by Giri et al. (2018), Ooi et al. (2014) and Arnhardt et al. (2007). Nevertheless, before using them in real cases it is necessary to validate their use in laboratory conditions.

The aim of this paper is to present the results of the first experiments performed with an experimental apparatus, also called a flume, developed for landslide simulation. The flume was filled with dry sandy soil with embedded accelerometers and the landslides were simulated by tilting the apparatus.

2 EXPERIMENTAL APPARATUS: TILTING FLUME

Figure 1 shows the “tilting flume” developed for the research. It´s dimensions are: 160 cm long, 50 cm wide and 50 cm deep and it was built with steel and one side of glass, which allows soil observation during the experiments. The apparatus can be tilted up to 45º with a hydraulic jack. In figure 1 three sections are indicated, namely “Lower part”, “Intermediate part” and “Upper part”. These terms will be used in the text to explain the position of the sensors, but there are no internal divisions in the flume.

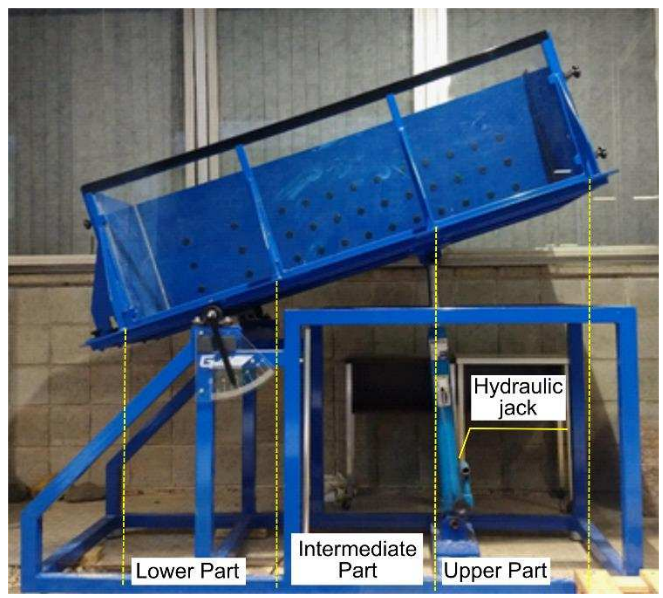

Figure 1 Tilting flume developed for the research.

3 LANDSLIDE SIMULATION EXPERIMENTS

Landslide simulation experiments were performed using dry sandy soil. Characteristics of the soil that was used, the setup of the experiment and the results achieved are described in the following items.

3.1 Soil material tested

The soil used in this research is a uniform medium sand, with a mean particle diameter of 0.27mm and composition of 96.1% of silica. According to the Unified Soil Classification System (USCS), the soil is classified as poorly graded sand. Table 1 presents the properties of the soil used in the experiments and Figure 2, the grain-size distribution curve.

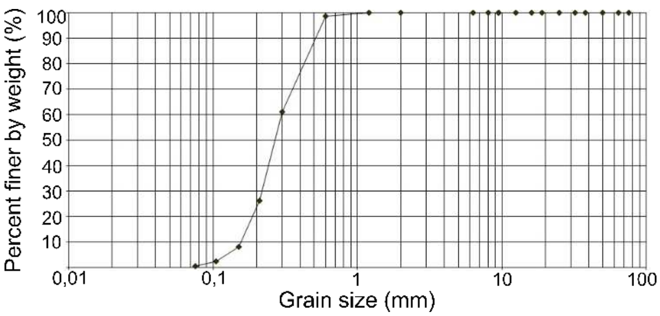

Figure 2 Grain-size distribution of the tested soil.

Table 1 Characteristics of the tested soil.

Soil parameter	Value
D_{10} – Effective grain size	0.16
D_{30}	0.22
D_{60}	0.30
U_c – Uniformity coefficient	1.90
e_{max} – Maximum void ratio	0.92
e_{min} – Minimum void ratio	0.70
ρ_{dmax} – Maximum dry density[1]	1.564 g/cm^3
ρ_{dmin} – Minimum dry density[2]	1.380 g/cm^3
G_s – Specific gravity of solids	2.653

[1] Estimated according to the Brazilian Standard Code ABNT/12.004/1990;
[2] Estimated according to the Brazilian Standard Code ABNT/12.051/1991;

3.2 Experiment setup

Two experiments were conducted with a 30cm thick layer of sandy dry soil compacted to its maximum specific gravity. Soil was compacted manually with a wooden hammer.

A piece of 160cm long x 50cm wide geosynthetic "Basetrac Woven 25", with standard biaxial tensile strength of 80 kN/m^2, was placed at 10 cm depth in order to reduce the occurrence of translational slides and to developed a weaker interface along which failure could happen.

Two types of accelerometer, called in this paper High Frequency Accelerometer (HFA) and Low Frequency Accelerometer (LFA) were embedded in the soil. They differ from one another in terms of sampling frequency, range, axis quantity and dimensions. HFA (Analog Devices, ADXL-321) works with 400Hz sampling frequency, +/- 18g range and is biaxial whereas LFA (ST, LIS331DLH) works with 1Hz sampling frequency, +/-2g range and is triaxial. Their dimensions can be seen in Figures 3 and 4, respectively.

To collect data, HFA were connected with wires to a datalogger, which was connected to a computer. LFA collected data in a memory card and transmitted data in real time, via wi-fi.

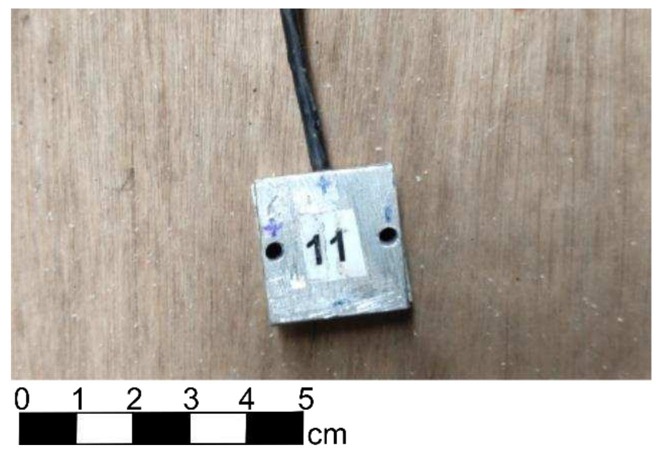

Figure 3 High frequency accelerometer (HFA).

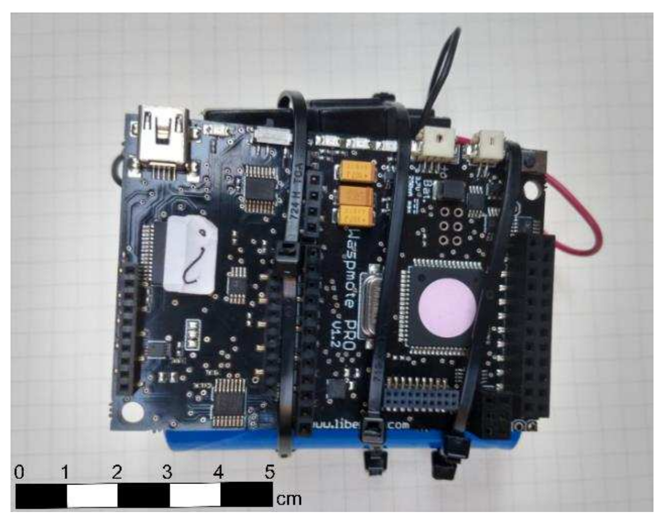

Figure 4 Low frequency accelerometer (LFA).

3.2.1 First Experiment

For the first experiment, six HFA and one LFA were used, as showed in Figure 5. One HFA (n. 6) was fixed on the external wall of the flume, in order to be a reference of no movement of the soil.

The experiment begun by tilting the flume until 32º. After this, the tilting angle was increased in 2º until 38º, when small and localized shallow landslides started to happen. At 39º, shallow landslides started to happen all over the surface and at 40º, final macroscopic failure happened along the soil-geosynthetic interface. Table 2 summarizes the procedure and the macroscopic observations for this experiment.

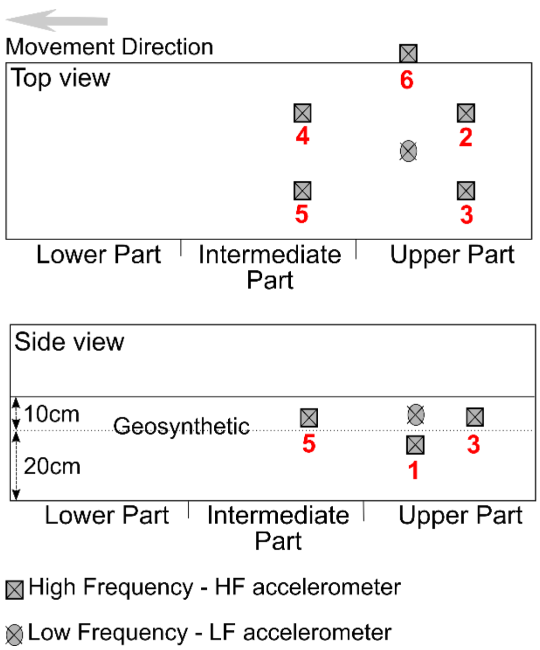

Figure 5 Accelerometers positions during the first experiment.

Table 2 Tilting procedure and observations during the first experiment.

Event	Tilting angle	Macroscopic observations
A	32º	-
B	34º	-
C	36º	-
D	38º	Small and localized shallow landslides
E	39º	Generalized shallow landslides
F	40º	Macroscopic failure

3.2.2 Second Experiment

Six HFA and two LFA were used in the second experiment. Figure 6 presents the experiment setup. As in the first experiment, one of the HFA accelerometers was used as no movement signal reference (n. 6). Differently from the first experiment, in the second one there were used two LFA devices, with different acquisition system: one LFA device collected data with its memory card and the other one, transmitted in real time. However, the results of comparison of the data collection systems will not be discussed in this paper.

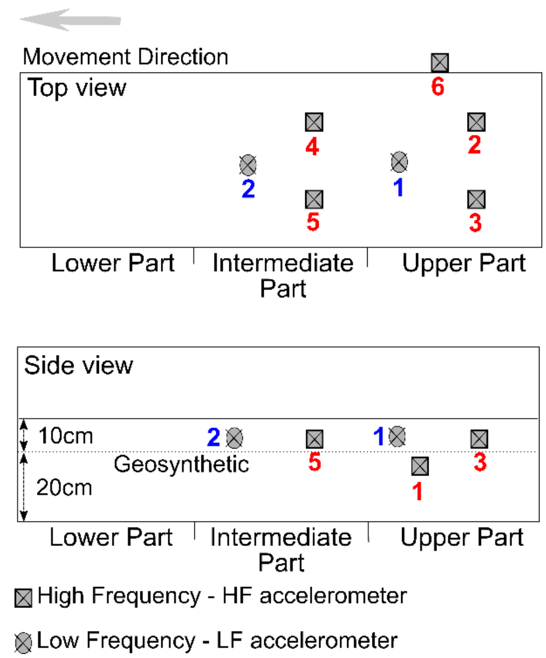

Figure 6 Accelerometers positions during the second experiment.

Table 3 presents the tilting procedure and the macroscopic observations. The tilting procedure and the placement of the second LFA accelerometer were the only intended differences between the two experiments. Nevertheless, possibly due to the different tilting stages, the failure in both experiments was not exactly the same. In the second experiment shallow landslides started to happen at 34º. Final macroscopic failure happened at 41º, along the soil-geosynthetic interface.

Table 3 Tilting procedure and observations during the second experiment.

Event	Tilting angle	Macroscopic observations
A	32º	-
B	34º	Shallow and localized landslides on the upper part
C	36º	Generalized shallow landslides

D	37º	Shallow and localized landslides on the upper part
E	38º	Generalized shallow landslides
F	39º	Generalized shallow landslides
G	40º	Generalized shallow landslides
H	41º	Macroscopic failure in the upper part

4 RESULTS AND DISCUSSION

4.1 First Experiment

In the first experiment both accelerometer types were able to measure accelerations during the failure, meaning that HFA and LFA moved together with the soil during landslide. Nevertheless, neither of them identified pre-failure signals, as it can be seen in Figure 7 and Figure 8, where high acceleration peaks correspond to the failure moment and no acceleration anomalies were measured before the failure.

Data presented in Figure 7 and Figure 8 correspond to acceleration in the axis parallel to the movement direction. Acceleration measured coincides with the component of the gravity measured in this axis and is always less than 1*g*.

By analyzing the data collected by the accelerometers it was possible to conclude that landslide started in the intermediate part of the flume and propagated to the upper part, as HFA numbers 4 and 5 registered movement approximately 1 second after the flume was tilted to 40º, whereas HFA numbers 2 and 3 detected failure after 4 seconds (Figure 8).

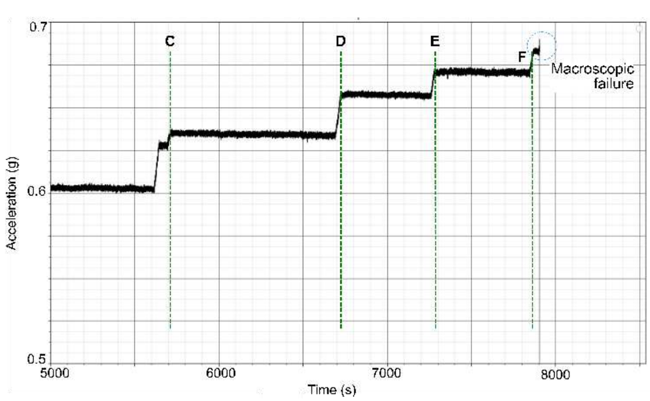

Figure 7 Acceleration measured with HFA-3 during the first experiment. Letters C to F with green lines correspond to the end of tilting events, showed in Table 2.

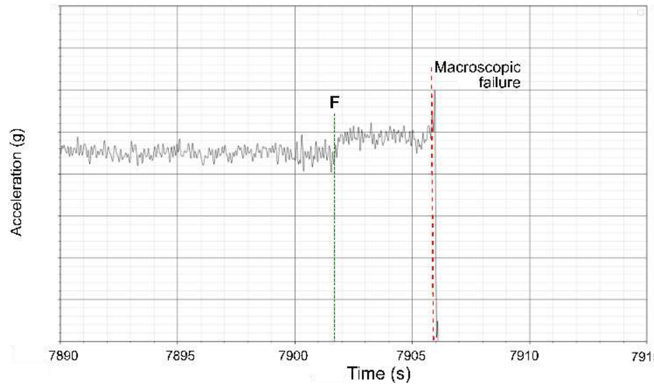

Figure 8 Detail of acceleration measured with HFA-3 in the axis parallel to the movement, close to macroscopic failure moment. Letter F corresponds to the end of the tilting 41º event, before the macroscopic failure.

4.2 Second Experiment

In the second experiment the macroscopic failure was observed only in the upper part of the flume. As a result of the landslide dimensions, only HFA numbers 2 and 3, located in the upper part of the flume, moved with the soil.

Pre-failure signals were identified with HFA 2 and 3: both started to detect anomalous accelerations 4 and 5 seconds after the flume was at 41º, respectively. Those signals were measured for almost 5 and 4 seconds, respectively, and then macroscopic failure happened, as showed in Figure 9 to Figure 12.

Those results show that it is possible to detect landslide pre-failure signals with accelerometers.

Data presented in Figure 9 to Figure 12 correspond to acceleration in the axis parallel to the movement direction. As it is the acceleration measured in one axis it is always less than 1*g*.

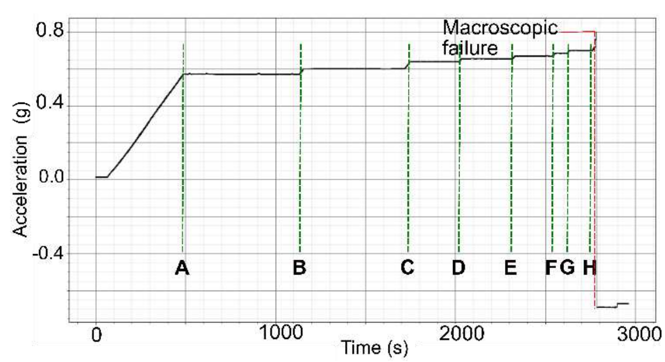

Figure 9 Acceleration measured with HFA-2 during the second experiment, in the axis parallel to the movement. Letters A to H correspond to the end of tilting events, showed in Table 3.

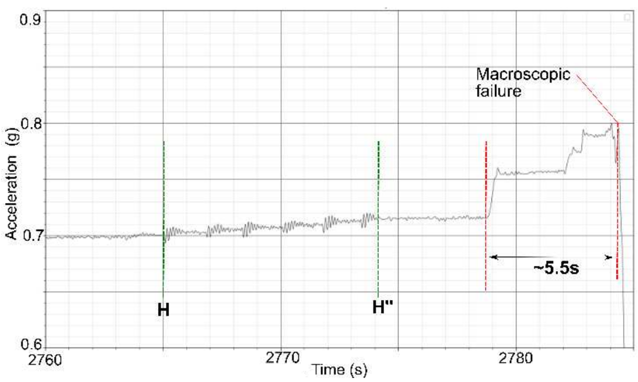

Figure 10 Detail of acceleration measured with HFA-2 in the axis parallel to the movement, close to macroscopic failure moment. Letters H' and H'' correspond to the beginning and the end of the 41° tilting event. Note the change in acceleration absolute value and pattern

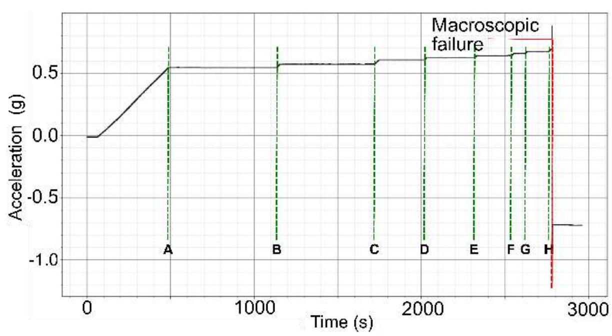

Figure 11 Acceleration measured with HFA-3 during the second experiment, in the axis parallel to the movement. Letters A to H correspond to the end of the tilting events showed in Table 3.

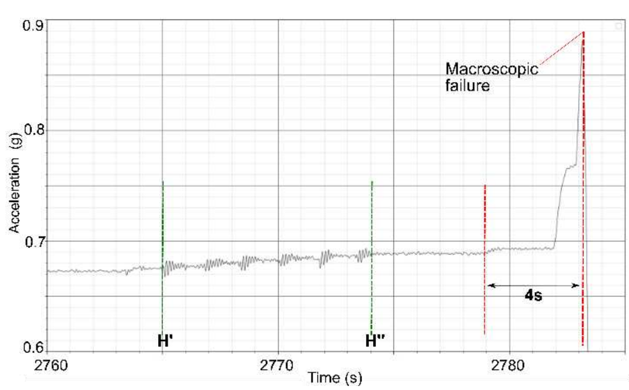

Figure 12 Detail of acceleration measured with HFA-3 in the axis parallel to the movement, close to macroscopic failure moment. Letters H' and H'' correspond to the beginning and the end of the 41° tilting event. Note the change in acceleration absolute value and pattern.

5 CONCLUSION

This paper presented the results of experiments designed to test the use of accelerometers as sensor nodes in an EWS for landslides.

Two landslide simulation experiments were performed in a flume using dry sandy soil. Two types of accelerometers with different sampling frequency, amplitude range, axis quantity and dimensions were embedded in the soil during the experiments.

In the first experiment, both accelerometer types identified the failure although no pre-failure signals were detected. Acceleration results showed that failure surface started to develop from the intermediate part and spread to the upper part of the flume, since accelerometers located in the intermediate part detected the failure 3 seconds before those located in the upper part.

In the second experiment, only two HFA moved together with the soil, as the simulated landslide occurred in the upper part of the flume and was identified only by the two HFA deployed in this location.

Pre-failure signals were detected approximately 4 to 5 seconds before the rupture in the data collected by those two accelerometers.

The results of both experiments suggest that accelerometers should be used more frequently in landslide research, because they can provide information about the development of the landslide and landslide mechanism.

Regarding their deployment in EWS, these first results presented in this paper suggest that it is possible to detect changes in the acceleration pattern that may be precursors indicative of the failure. Future work on the subject is needed and include performing experiments in wet conditions, in order to simulate rainfall triggered landslides.

6 ACKNOWLEDGMENTS

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