Geo-electrical monitoring of rainfall triggered landslides at the laboratory scale

Greta Tresoldi ([a]), Diego Arosio ([b]), Davide Brambilla ([a]), Azadeh Hojat ([a, c]), Vladislav Ivov Ivanov ([a]), Laura Longoni ([a]),
Monica Papini ([a]), Marco Scaioni ([a]) & Luigi Zanzi ([a])

([a]) Dipartimento di Ingegneria Civile e Ambientale, Politecnico di Milano, Piazza Leonardo Da Vinci 32, 20133 Milano, Italy; greta.tresoldi@polimi.it
([b]) Dipartimento di Scienze Chimiche e Geologiche, Università di Modena e Reggio Emilia, Via Giuseppe Campi 103, 41125 Modena, Italy
([c]) Department of Mining Engineering, Shahid Bahonar University of Kerman, Jomhouri boulevard, Kerman, Iran

Document type: Extended abstract.
Manuscript history: received …………. 20xx; accepted ………….. 20xx;

ABSTRACT

To study shallow landslides triggered by rainfall events, a scaled down model of landslide was reproduced in a landslide simulator designed by the “Geophysical and Geological Lab” of Politecnico di Milano, Lecco Campus. Different geo-engineering techniques including geological surveying, photogrammetry, topography surveying and geophysics were used to monitor the event and to forecast the failure process after recognizing precursors of the event.

In this work time-lapse ERT measurements were implemented at the laboratory scale and the results were analyzed in order to monitor rainwater infiltration in the landslide body and to determine precursors of the failure. Inverted resistivity sections can indicate inhomogeneous saturation zones within the slope body, as well as clearly recognize fractured zones long before the collapse.

We calibrated a relation that links inverted resistivity values to water saturation and thus, we could obtain saturation maps to analyze the landslide activity in terms of soil water content. Defining saturation thresholds which result in slope failure of shallow landslides, a monitoring system based on resistivity measurements can be coupled with a warning procedure to underline zones prone to failure before the collapse

KEY WORDS: ERT measurements, geo-electrical monitoring, laboratory test, shallow landslides, resistivity, scaled model, time lapse measurements, landslide precursors, saturation thresholds, water saturation.

INTRODUCTION

Shallow landslides triggered by rainfalls can cause serious economic damages and make attempt on human lives. The slope failure can develop rapidly and is mainly related to anomalous precipitation events. Therefore, rapid water saturation caused by rainfalls is one of the most important triggering factors of shallow landslides and thus monitoring the soil water content can be very important to predict landslide events.

In last decades, geophysical techniques were applied to landslide or artificial earth structure monitoring and prevention with great results; for example, time lapse electrical resistivity tomography (ERT) measurements were implemented in different cases to track water infiltration and underline detachment zones (Piegari et al., 2008; Supper et al, 2009; Niesner, 2010; Di Maio & Piegari, 2011; Perrone et al., 2014; Supper et al, 2014; Arosio et al., 2017; Tresoldi et al., 2018), but laboratory tests involving slope instability and geo-electrical methods have not been implemented so far. Moreover, due to the complexity of the real domain and the difficulty in quantification of water saturation on an extended soil, the saturation thresholds that can lead to instability have not been defined yet at the field scale.

In order to determine saturation thresholds that can initiate a landslide phenomenon, a small scale landslide was constructed in a landslide simulator designed by the “Applied Geophysical and Geological Lab” of Politecnico di Milano, Lecco Campus. Integrating different geo-engineering techniques such as geology, photogrammetry, topography surveying and geophysics was possible to analyze and study the shallow landslide body during simulated rainfall events.

In this work, geo-electrical time-lapse measurements are described as an efficient tools to map the variations of soil saturation and to predict and prevent shallow landslides. This is due to the fact that resistivity measurements are sensitive to changes of water content with time. Investigations at the laboratory scale are useful to underline the potential of the

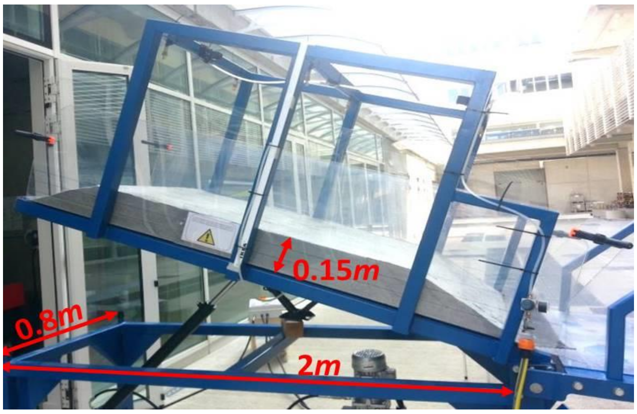

Fig. 1 – Geometry of the landslide simulator and sand layer.

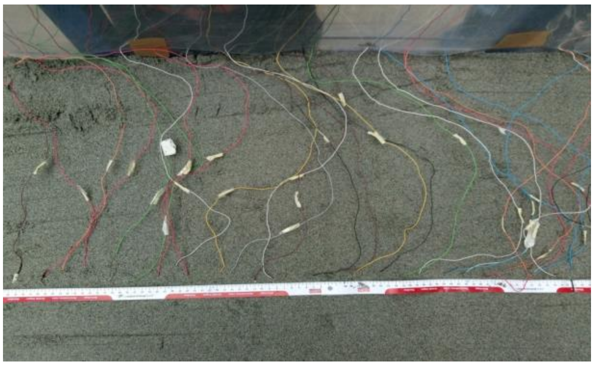

Fig. 2 – Miniaturized cables and electrodes deployed on the landslide body before being buried under 1cm of sand.

method, knowing all parameters about soil characteristics and the geometry of the slope, as well as boundary conditions.

MATERIALS AND METHODS

A landslide simulator was designed with a base of 2m × 0.80m with the possibility of being inclined to reproduce the slope. To simulate rainfalls, six sprinklers were placed on the top frame of the flume (Fig. 1).

Four laboratory tests were carried out during May and June 2017, with similar landslide geometry but different rainfall intensities and monitoring settings to define the best configuration of measurements. The shallow landslide was designed to reproduce a real event, using a sand with the porosity of 54% deployed in a layer of 0.15m thick. This geometry was calculated to satisfy the condition of unlimited slope, with h/L<10, where h is the thickness of the layer and L is the length of the landslide body. The slope angle was set in the range of 35°-40° for different tests.

To perform ERT measurements at the laboratory scale, a miniaturized system was built to be compatible with the resistivity-meter IRIS Syscal Pro: two 24-channel cables (each1.40m long) equipped with 48 2cm-long stainless steel electrodes with a diameter of 2mm were prepared. Cables and electrodes were placed parallel to the slope in the central part of the landslide body, buried at the depth of 1cm so that the electrodes would not produce preferential pathways for infiltration of the rainwater (Fig. 2). A Wenner configuration was implemented with a minimum electrode spacing of 3cm in order to obtain vertical and horizontal data resolution of 1.5cm and 3cm, respectively. Using two separate cables, it was possible to continue measurements with the remaining 24 electrodes placed in the top part after the collapse of the inferior part of the slope.

To measure the water content variations with time and to correlate saturation values with inverted resistivity values through a petrophysical relation, a TDR probe was embedded in the landslide body. Two cameras were also installed on the top part of the flume to link times of failures with the precursors underlined by monitoring data.

In different tests, time-lapse ERT profiles were measured every 10min during the infiltration of rainwater until the complete failure of the slope. Having a sequence of measurements makes it possible to monitor the variations in water saturation and to find precursors of the starting point of the failure process.

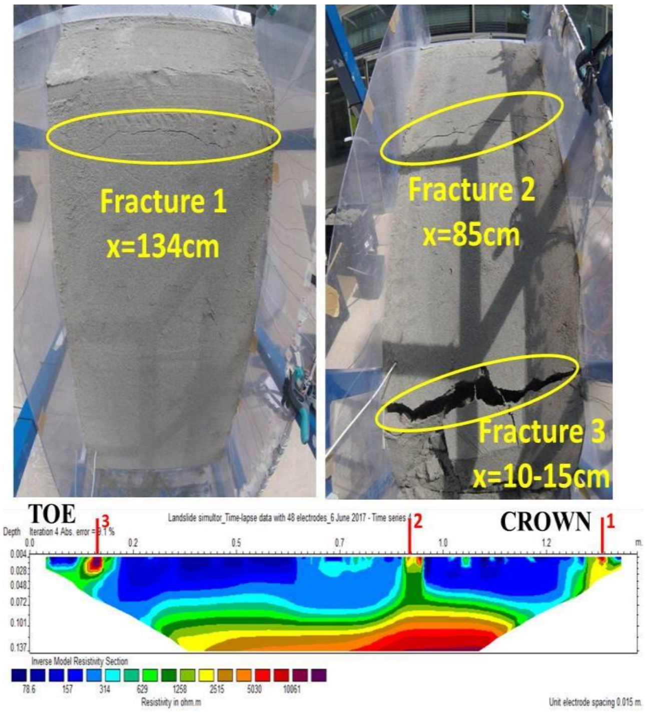

Fig. 3 – Fracture zones with their positions in the landslide body and mapped in the inverted resistivity section.

RESULTS AND DISCUSSION

The inverted time-lapse resistivity sections could detect rainwater paths and accumulation zones due to different soil compaction; from the data measured before beginning the rainfall (named T0), information about inhomogeneity of the landslide body could be deducted, while sections measured during the rainfall event underlined different zones of infiltration.

What emerged was that the infiltration process was not homogeneous and zones that appeared less compacted at T0 experimented a major accumulation of water. All these processes could be well monitored using the inverted resistivity sections obtained at different times from beginning of the tests.

Time-lapse ERT measurements were also used to highlight weak zones created during the tests, thanks to a comparison with the images captured by the two cameras. Every image at the time of the development of a crack was analyzed to obtain the position of the weak zone and to correlate it with the inverted resistivity section measured in that time. We saw that fracture zones were well indicated by high resistivity values – due to the presence of resistive air - long before the opening of the fractures and the final collapse of the slope (Fig. 3). One of the future perspectives is to convert the time from appearance of weak zones until their collapse, from the laboratory scale into a real period of time, in order to use it for implementing an early warning procedure.

In order to relate resistivity values to water saturation values, the Archie law (Archie, 1942) was calibrated using volumetric water content data from the TDR probe, resistivity of water, soil resistivity and soil characteristics. Every resistivity section was then transformed into a water saturation map (Fig. 4), with the aim of recognizing water saturation values that can lead to instability.

The results showed that detachment zones appear at the borders of different saturated zones (Fig. 5), probably due the different weight of the soil, while after a certain value of water saturation (more than 40%) fractures were developed in the most saturated parts (Fig. 6).

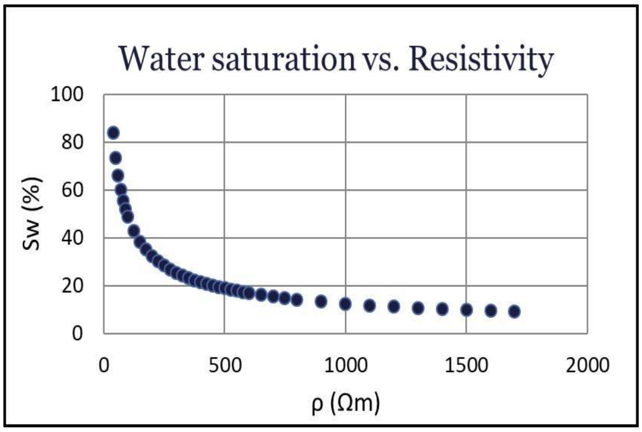

Fig. 4 – Water saturation vs. resistivity calculated from calibration of Archie law.

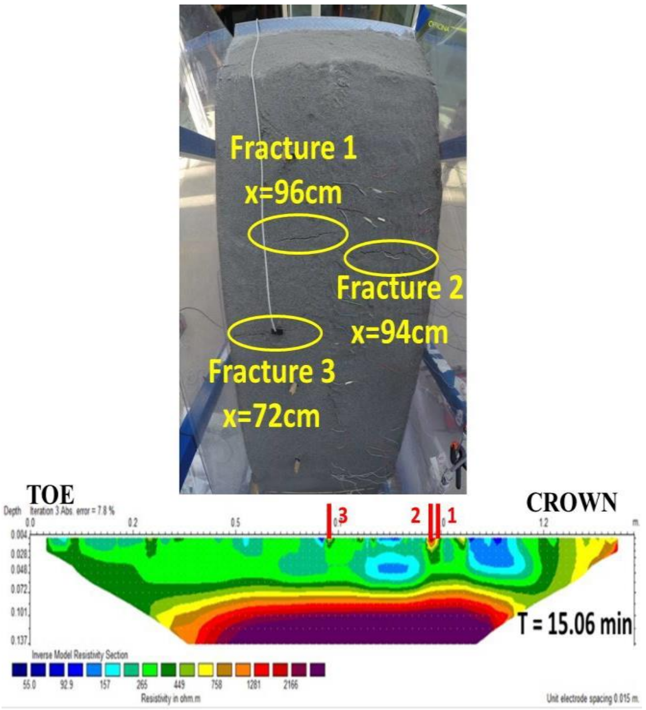

Fig. 5 –. Fracture zones with their positions in the landslide body and mapped in an inverted resistivity section at the borders of non-homogenous zones.

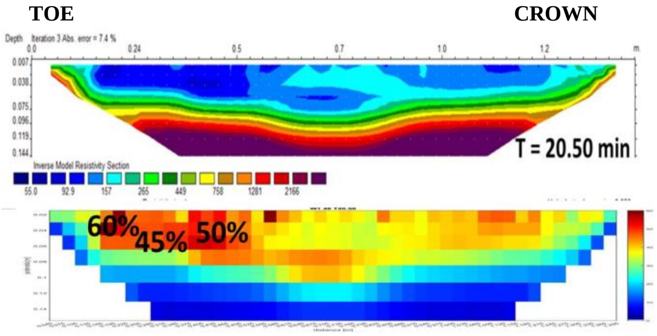

Fig. 6 – Transformation of an inverted resistivity section into a water saturation map: a highly saturated part that would undergo a failure process is highlighted.

Considering different possibilities of activation process – caused by non-homogeneous parts and very saturated zones – it was not possible to find a unique value of water saturation that could be defined as a precursor of failure for the soil type and slope angle used in our experiments. However, inhomogeneity of the landslide body appeared to be one of the most critical factors, because it could influence the infiltration of rainwater and lead to differential movements of the soil.

One of the limitations of the ERT measurements was the low frequency of measurements due to the time required for each acquisition. This can result in misunderstanding of the processes and missing of information. A key point in rapid monitoring sequences is to find a suitable time lapse between each measurement. Therefore, a monitoring station capable of operating and being programmed remotely can play a very important role in monitoring of landslides.

Another important factor is that the measurements have to be quite rapid to follow a fast process such as the failure of a rainfall triggered landslide without any aliasing: in order to make ERT technique as fast as possible, a high speed configuration must be implemented.

In some cases, the failure occurred just in the point where the measurement was being executed, giving very high values as a result. Those values could be used as a warning to indicate that a sliding process is happening. Having the possibility of continuing measurements after a partial failure of the slope, the situation could be monitored in the more elevated part remained in place, obtaining information about the progression of the landslide event.

CONCLUSIONS

Time-lapse resistivity measurements have shown to be a suitable method to monitor shallow landslides, since the principal triggering factor is rainwater infiltration.

During the laboratory tests carried out in this work, a small scaled shallow landslide was built in a landslide simulator designed for the purpose.

Applying a geo-electrical monitoring at the laboratory scale, with miniaturized cables and electrodes, was possible to underline inhomogeneity of the landslide body and to track rainwater pathways inside the slope during a simulated rainfall event with changing intensities.

A relation between inverted resistivity values and water saturation of the soil was calibrated using the petrophysical Archie law, thanks to volumetric water content values from a TDR probe. All inverted resistivity sections were then transformed into saturation maps.

Resistivity and saturation sections were used to find precursors of failure. The results showed that weak zones can be easily recognized due to their high resistivity values long before the final collapse.

These detachment zones were initially mapped at the borders of different saturated parts or, after, when saturation reached high values (more than 40%).

In order to find thresholds of water saturation that can be considered as triggering factors for activation of landslides, more laboratory tests should be performed using different slope angles and different soil types.

The frequency and the speed of measurements play an important role in the possibility of recognizing fast phenomena, such as the activation of a shallow landslide without aliasing. As a future development, high speed data acquisition must be considered in geo-electrical monitoring.

Geo-electrical time-lapse measurements could be used successfully to describe the hydraulic and geotechnical situation of a landslide body and can track changes in soil water content with time. More work is needed to set water saturation thresholds as precursors of failure and to use them to implement an early-waring procedure.

ACKNOWLEDGMENTS

This research was partially funded by Fondazione Cariplo, grant n° 2016-0785.

REFERENCES

Archie G. E. (1942) - The electrical resistivity log as an aid in determining some reservoir characteristics. Petr. Transact. of AIME, 146, 54–62.

Arosio D., Munda S., Tresoldi G., Papini M., Longoni L. & Zanzi L. (2017) - A customized resistivity system for monitoring saturation and seepage in earthen levees: installation and validation. Open Geosciences, 9, 457-467, doi: 10.1515/geo-2017-0035.

Di Maio R. & Piegari E. (2011) - Water storage mapping of pyroclastic covers through electrical resistivity measurements. Journal of Applied Geophysics, 75, 196-202.

Niesner E. (2010) - Subsurface resistivity changes and triggering influences detected by continuous geoelectrical monitoring. Lead. Edge, 29, 952-955.

Perrone A., Lapenna V. & Piscitelli S. (2014) - Electrical resistivity tomography technique for landslide investigation: A review. Earth-Sci. Rev., 135, 65.

Piegari E., Cataudella V., Di Maio R., Milano L., Nicodemi M. & Soldovieri M. G. (2008) - Electrical resistivity tomography and statistical analysis in landslide modelling: A conceptual approach. J. of Appl. Geophys., 68, 2, 151–158.

Supper R., Römer A. & Jochum B. (2009) - Geoelectrical measurements for natural hazard monitoring. Proceedings of the 9th SEGJ International Symposium, Sapporo, Japan, 12-14 October 2009, 1-4.

Supper R., Ottowitz D., Jochum B., Kim J.-H, Romer A., Baron I., Pfeiler S., Lovisolo M., Gruber S. & Vecchiotti F. (2014) - Geoelectrical monitoring: An innovative method to supplement landslide surveillance and early warning. Near Surf. Geophys., 12, 1, 133-150. Doi: 10.3997/1873-0604.2013060.

Tresoldi G., Arosio D., Hojat A., Longoni L., Papini M. & Zanzi L. (2018) - Tech-Levee-Watch: experimenting an integrated geophysical system for stability assessment of levees. Rendiconti Online della Società Geologica Italiana (in press).