Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL079724

Acoustic Emissions and Microseismicity in Granular Slopes Prior to Failure and Flow-Like Motion: The Potential for Early Warning

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Abstract Rain-triggered landslides in loosely packed granular deposits are highly hazardous because of their sudden failure, flow-like motion, and high mobility. Predicting their initiation and establishing monitoring and early-warning strategies based on the actual mechanisms of failure, rather than on statistical-empirical relations, can be challenging. Experiments on artificial granular slopes revealed a systematic instability-triggering process entailing the internal erosion and seepage-driven transport of small grains. This rearrangement of matter generates acoustic signals and microseismicity detectable prior to any pore water pressures spikes or macroscopic deformations, which are common proxies for slope stability monitoring. Acoustic emissions are more pronounced in loose assemblies, while they are much weaker in densely packed mixtures, which will not exhibit fluid-like motion. Acoustic sensors and accelerometers in support to monitoring networks for flow-like landslides can improve our early warning capabilities, as long as their good performance is confirmed in real-scale applications.

Plain Language Summary Some landslides initiated by rainfalls and evolving into very fast and destructive fluid-like movements are hardly predictable because they happen suddenly, with little warning. Traditional monitoring systems might fail to capture precursory signals, and thus, timely alarms cannot always be released. These systems mostly rely on known correlations between the amount and intensity of rainfall and the occurrence of landslides in the past or on the detection of water level and pressure changes by instruments installed within the slopes. However, these changes are often detected late, when the movement is already accelerating dramatically. In our experiments, we found that one of the processes that trigger flow-like landslides in granular soils is the internal erosion of small soil particles transported by water flowing within the slopes. This produces measurable vibrations (microseismicity) and sounds (acoustic emissions) well before water pressure changes and deformation trends can be identified. The performance of real-scale acoustic and seismic monitoring systems is still being verified, but we believe that complementing slopes monitoring with acoustic and seismic sensors can be the winning strategy to provide more timely alarms to evacuate people along the landslide paths and save more lives.

1. Introduction

Acoustic emission (AE) is a well-known phenomenon in rock masses undergoing inelastic processes under hydro-thermo-mechanical forcing. It has been investigated extensively to understand the mechanisms of rock failure and those of natural and induced seismicity (Amitrano et al., 2012; Goodfellow & Young, 2014; Grgic & Amitrano, 2009; Griffiths et al., 2018; Petružálek et al., 2018; Zhao et al., 2015). In granular materials AE are generated through various processes, including sliding and rolling friction, contact stress release due to the overcome of interlocking, collisions, rearrangement of contact networks, and crushing of grains (Berg et al., 2018; Collins & Melosh, 2003; Davies et al., 2012; Ferdowsi et al., 2013; Jiang et al., 2017; Johnson et al., 2013; Mao et al., 2016; Michlmayr et al., 2013). These events generate elastic waves usually in the kilohertz to megahertz frequency range. Processes at different scales produce distinct frequency and energy signatures, enabling the use of AEs to assess the mechanical state of complex materials and granular flows (Michlmayr et al., 2013). Laboratory and field tests revealed correlations between shear strain rates and AE rates in granular assemblies. Acoustic signatures of incipient failures were identified in some cases (Berg et al., 2018; Dixon et al., 2018; Jiang et al., 2017; Smith et al., 2017). Monitoring soil slopes through AEs has been recently suggested as a low-cost and time-effective approach for continuous monitoring and...
early warning of some slow movements and first-time failures in some materials (Dixon et al., 2018; Faillettaz et al., 2016; Michlmayr et al., 2017; Smith et al., 2014, 2017; Stähli et al., 2015).

Microseismicity (MS) can originate from the same processes that produce AEs but is characterized by lower frequencies (hertz to kilohertz). The smaller attenuation during propagation facilitates their detection at larger distances. However, lower frequencies imply larger source sizes: in rocks, MS comes from events of meter to kilometer size, while AEs relate to sizes of millimeters to decimeters (Amirniano et al., 2012). Seismic wave velocities in soils are generally lower than in rocks. At a given frequency, this translates into smaller source sizes. MS in soils may thus signal sources down to millimeter size (Bartake & Singh, 2007; Hu, Hicher, et al., 2018; Sellers et al., 2003; Wei et al., 1996). The high-energy component of MS from granular slopes, filtered through empirical mode decomposition and instantaneous frequencies determination (Hilbert-Huang transform; N. E. Huang et al., 1998), has been associated to interparticle slip and microstructural rearrangements (Hu, Hicher, et al., 2018). Yan et al. (2017) also related different frequency bands to different processes occurring prior to and upon failure of a landslide dam. Hu, Scaringi, et al. (2018) suggested that MS in some granular assemblies can be related to the internal erosion of small grains migrating through large-pore networks and triggering microstructural changes. Because MS was recorded prior to any pore water pressure spikes upon failure (Hu, Hicher, et al., 2018; Hu, Scaringi, et al., 2018), it was suggested that increasing levels of MS can signal incipient instability in loose granular slopes. However, the physical links between MS and the grain-scale processes leading to failure and fluidization deserve further investigation, while they are more apparent for AEs (Michlmayr et al., 2013).

2. Motivation

Large flow-like landslides can cause severe damage and fatalities (Dowling & Santi, 2014) due to their high mobility and sudden failure that can baffle alarm systems tuned on measurements of rainfall, deformation, pore water pressure, suction, or groundwater level. Partial or complete fluidization of the moving mass and/or the overridden bed material is a possible cause of flow-like landsliding in granular materials and in some cohesive soils (Cascini et al., 2008; Geertsema & Torrance, 2005; Iverson et al., 2000; Iverson & George, 2016; Peng et al., 2018; Picarelli et al., 2008). Flow-like motion and long runout can result also from other shear-rate-weakening mechanisms that do not involve liquefaction (Hu, Xu, et al., 2017; Scaringi et al., 2017, 2018; M. Zhang & McSaveney, 2017). Flow-like landsliding can occur with enhanced frequency after strong earthquakes (Doménech et al., 2018; Fan, Doménech, et al., 2018; R. Huang & Fan, 2013). Earthquake-triggered landslides can generate masses of debris that are generally well graded due to heavy fragmentation during runout (S. Zhang et al., 2014; X. Zhang et al., 2018) but are loosely deposited on steep slopes with marginal stability. Subsequent rain-triggered failures evolving into flow-like landslides are common in these deposits, and their frequency can remain high for several years (Doménech et al., 2018; Fan, Juang, et al., 2018). These failures can be preceded by microstructural rearrangements, with contractive behavior that generates pore pressure excess and can cause a general collapse. Variously graded and packed materials will exhibit different motion patterns depending on their ability to dissipate the pressure excess (Iverson et al., 2010; Wang & Sassa, 2003). Significant increases of MS were recorded prior to measurable deformations and pressure excess during experiments on artificial slopes (Hu, Hicher, et al., 2018, Hu, Scaringi, et al., 2018). AEs were also related to mechanical failure in ring-shear friction experiments (Jiang et al., 2017). Here to investigate possible improvements to our early warning capabilities for flow-like landslides, we focus on MS and AEs recorded from artificial slopes, the failure of which was induced by progressive water saturation. We show the systematic ability of MS and AEs to serve as failure precursors and compare their patterns to those of pore water pressures and deformations. Finally, we discuss benefits and challenges of employing these measurements for early warning, also in the light of other recent contributions from the literature.

3. Materials and Methods

The experiments were performed on artificial slopes assembled in a flume (Figure 1). These slopes were 110 cm long at the floor, 65 cm long at the top, and 25 cm thick; the flume was 3 m long, 0.4 m wide, and inclined 28° from the horizontal. This angle was chosen to allow for various behaviors to be reproduced and is consistent with that of the slopes where coseismic debris accumulated in the region hit by the 2008
Mw 7.9 Wenchuan earthquake in Sichuan, China (Hu, Scaringi, et al., 2018). Slope failure was induced by a constant water head (15 cm) at the back of the slopes. The impervious, roughened bottom of the flume was equipped with five pore pressure transducers, installed at regular intervals (10, 30, 50, 70, and 90 cm from the back of the slope) along its median longitudinal section. A 2-cm styrene foam ball connected to a displacement transducer and appropriately counterweighted was used to measure internal displacements at a single location in the middle of the slope. MS was recorded by a 100-V/g accelerometer (Wilcoxon-731A/P31) installed under the floor and sampled at 1 kHz; AEs (100–400 kHz) were recorded through a high-sensitivity wideband transducer (Physical Acoustics, Mistral Group, Inc.) with 40-dB amplification installed on one sidewall and sampled at 1 MHz. A Ni-CompactDAQ (National Instruments) acquisition system assured synchronized recording.

The granular soil was sampled from a deposit of coseismic debris in Wenjia gully, where numerous rain-induced failures and destructive debris flows occurred (Xu et al., 2012). The soil, made of limestone fragments, was generated by dynamic fragmentation during a coseismic rock avalanche (Xing et al., 2017; Xu et al., 2012; M. Zhang et al., 2016). It has a specific gravity $G = 2.62$ and grain sizes from gravel to silt. The soil was partitioned into large and small particles (threshold: $d = 0.5$ mm), which were remixed to obtain the experimental grading (Figure 2a). This threshold was chosen following the sizes of particles that were internally eroded and transported by water seepage, as determined in preliminary experiments (Hu, Scaringi, et al., 2018).

We chose a mixture containing 16% small particles, prepared at a gravimetric water content $w = 5\%$. If loosely packed, this mixture can fail suddenly and exhibit flow-like motion under various hydraulic conditions (Hu, Scaringi, et al., 2018). The mixture was transferred into the flume and compacted layer by layer to obtain skeleton relative densities $R_D$ varying from 0.03 to 0.95, with $R_D = (e_{max} - e_s)/(e_{max} - e_{min})$, where $e_s$ is the skeleton void ratio, $R_D = 0$ defines the loosest state $e_s = e_{max}$, and $R_D = 1$ defines the densest state $e_s = e_{min}$ (Text S1 in the supporting information; ASTM D4253–16, 2016; ASTM D7273–09, 2009; Chu & Leong, 2002; Kenney, 1977; Kuerbis et al., 1988; Mitchell, 1993). Steady state saturated hydraulic conductivity $k \approx 0.1$–0.2 mm/s was evaluated through tests in permeameter for this mixture in a wide range of $R_D$ (Figure 2b).
4. Results

Figure 3 summarizes the results of seven tests performed at different RDs. No failure occurred for RDs 0.81–0.95; at RDs = 0.69 the slope failed progressively but without fluidizing. At lower RDs, sudden failure occurred, with runout distances up to 1 m (Figure 4b) and velocities up to 1 m/s. Clearly, these values were constrained by the limited flume length. Details of monitoring data at failure are given for each experiment in Figures S1–S5 (supporting information); video footages are also provided (Movies S1–S5).

Pore water pressures at the floor (Figures 3a–3g) increased gradually as the slope became saturated. This increase was initially sharp, then gentler until a near steady state. Upon failure, pore pressure spikes were recorded especially in slopes with low RDs. These spikes did not precede macroscopic displacements (Figures 3h–3n; as in Hu, Scaringi, et al., 2018): high pore pressures developed upon failure, rather than being the trigger of it. Moreover, only small displacements preceded failure. This behavior is common in flow-like landslides; thus, it is apparent that early-warning strategies that rely solely on hydraulic and displacement measurements can fail in these conditions.

MS and AEs (Figures 3o–3u and S6–S10) can reveal more details of the internal slope processes heading to failure. Important MS was measured throughout the tests, as seen especially in the Hilbert-Huang transform of the first Intrinsic Mode Function, IMF1; Figures S6–S12), and its amplitude increased noticeably seconds before failure (see also Hu, Hicher, et al., 2018), with the whole tests lasting ~300 s. Small peaks well before failure also occurred, possibly associated to local internal collapses or structural readjustments. These were not accompanied by significant deformations but were revealed by small pore water pressure perturbations (Figures 3b, 3i, and 3p and Figures 3e, 3l, and 3s). At failure, MS amplitudes increased sharply, and significant MS persisted throughout the runout.

AE amplitudes increased much earlier (Figures 3o–3u), while pressures were still rising, and only negligible displacements were recorded: AE trends did not follow or resemble trends of these monitored quantities (as seen in Smith et al., 2014) but preceded them or occurred independently from them to some extent. Notably, the important AE amplitude increase only occurred in loosely packed slopes (those that eventually collapsed), while the pressure rise was not accompanied by significant AE in the densely packed ones. This signals the absence of internal erosion and structural rearrangements that lead to sudden failure. This was demonstrated by Hu, Scaringi, et al. (2018), who measured the soil grading at various locations in a densely packed slope (RDs 0.81), after failure did not occur during a test. Conversely, significant internal erosion, migration, and removal of small particles occurred in a loosely packed slope (RDs 0.19), whose grading was evaluated after arresting an experiment before failure.

Maximum AE amplitudes generally increased with time and peaked upon failure. Emissions were more frequent at low RDs, while the total acoustic energy was only weakly (negatively) correlated with RDs (Figure 4a). Conversely, the cumulated energy until failure showed a clearer positive correlation with RDs. In Figure 4b, runout distances and internal deformations prior to failure are reported: no clear pattern for the latter can be seen, while some negative correlation exists between final runout and RDs.

For the loosest assembly (RDs 0.03; Figure 3o), the AE pattern resembled somehow that of the pore pressure increase (Figure 3a), and intense AE activity continued also after failure. The cumulated acoustic energy showed a tertiary creep-like trend (Figure 3o), identifiable since the early stage of the tests and much clearer than that of the deformations (Figure 3h), possibly because the former is a cumulated measure while the latter are local measurements. This can be crucially important for full-scale slope monitoring, as the monitoring target would shift from point (= small volume) measurements to much larger soil volumes, thus blending the uncertainties deriving from local heterogeneities. Similar patterns of cumulated acoustic energy can be identified for higher RDs, although less clear due to disturbances caused by minor collapses (Figures 3p–3s).

For RDs 0.19 (Figure 3p) important AEs were recorded when positive pore pressures were also recorded at most locations along the floor (Figure 3b) but prior to any significant displacements (Figure 3i) or MS. For RDs 0.34–0.45 (Figures 3q and 3r) AEs were less frequent, but significant activity was still recorded while pore water pressures were still increasing (Figures 3c and 3d) and significant deformation (Figures 3j and 3k) or MS did not occur. The cumulated acoustic energy before failure for RDs 0.34 was especially small, reflecting the more sudden failure. Nevertheless, the progressive increase of AE activity was clearly identifiable during the 50 s preceding failure (with the test lasting ~100 s; Figure 3q). The same can be said for RDs 0.45 for which,
Figure 3. Pore water pressures along the flume floor (a–g), internal and surface displacements (h–n), and MS (acceleration) and AE (amplitude and cumulated energy) (o–u) recorded during the flume tests on mixtures with 16% small particles, packed at different RDs. MS = microseismicity; AE = acoustic emission; RDs = relative density.
Despite a different pressure pattern (possibly reflecting a localized liquefaction) and the absence of precursory deformations, AE is significant and intensifies in the 100 s preceding failure (test duration ~400 s; Figure 3r).

For RDs 0.69 (Figure 3s), the AE pattern followed the different slope failure mode, with small collapses prior to the general failure, also highlighted by significant MS and pore pressures perturbations (Figure 3e). The densely packed slopes (RDs 0.81–0.95) generated much less AEs and MS (Figures 3t and 3u); significant deformation and slope failure did not occur, notwithstanding pore water pressures that remained high much longer. Notice that the pattern of cumulated acoustic energy (Figure 3u) resembled that of a primary creep. For displacements or strains, this pattern underlies a progressive stabilization of the material, for which failure is not expected. The pattern of acoustic energy can thus be an insightful quantity for slope monitoring.

For additional investigation of the correlation among AEs, deformation, internal erosion, and particle migration, we performed some tests in which we replaced the fraction of small particles in the mixtures with common table salt (NaCl). The salt grains had dimensions compatible with those of the small particles, but, being highly soluble in water, they could mimic the process of internal erosion under lower porosities and hydraulic gradients, inducing structural rearrangements more promptly. In Figures 4c and 4d and Movies S6 and S7 we report the results of two tests during which failure did not occur: one was performed using a mixture containing small particles and the other using salt grains instead of small particles. Both mixtures were packed at RDs = 0.45 and placed in a flume inclined by 16°. This lower inclination and the resulting smaller hydraulic gradient produced a different behavior. Contrary to what happened to the identically packed mixture in the flume with 28° inclination (Figures 3d, 3k, and 3r), the two slopes did not fail. However, AEs were more frequent and energetic, and surface displacements (vertical settlements) were larger in the mixture with salt grains than in that with small particles (Figures 4c and 4d). This is consistent with a mechanism of structural rearrangement during water seepage caused by (extensive) salt dissolution in one case and by (minor) internal erosion in the other. It is worth noting that salt dissolution might have affected also the shear behavior of the assembly directly, thus enhancing the differences between the two
means that AE are actual failure precursors, activity can be detected even before the occurrence of measurable internal or surface displacements. This wish to point out that our experiments take a step further, as they demonstrate that significant acoustic emissions (AEs) can be detected before internal displacement of the slope along a preexisting shear zone or in a zone that was being formed. We reactivated landslides, and in all cases AE (produced by the amplifying medium) were correlated to the rates of internal displacement of the slope directly. Conversely, AEs (kilohertz to megahertz) can reveal particle-scale events, and their occurrence is detectable well before slope failure. Moreover, the patterns of AE amplitude (that increases when failure is approaching) and cumulated acoustic energy (with its creep-like shape) and the prefailure values of cumulated energy (Figures 3 and 4) can be calibrated on field observations and serve as early-warning thresholds. However, high-frequency AEs suffer important attenuations already at close distances; thus, the installation of dense monitoring networks or other strategies is required to achieve practical usability. Johnson et al. (2013) also provided independent experimental insight into the role of AEs as failure precursors. However, their results are not usable in our context because they used an experimental setting and explored a failure mechanism that differed significantly from those of our work. They studied stick-slip events (oscillating friction) in displacement-controlled conditions, with the purpose of forecasting fault motion, while we focused on shallow subsurface instability phenomena, that is, on dramatic failure events (with friction decreasing monotonically) that occur in practically force-controlled and stationary global-load conditions.

Smith et al. (2017) used a meter-size laboratory experiment for AE detection in simplified geometric and boundary conditions using active waveguides in a gravel-sized amplifying medium. They identified a good correlation between AEs and subsurface deformation rates in a shear zone (imposed by the experimental geometry), with AEs being able to identify the movement when rates are still slow (>0.5 mm/hr). In an earlier field trial on a reactivated slope movement, Smith et al. (2014) were also able to identify displacements occurring at as slow as 0.3 mm/hr because strain localization had already occurred. Field trials using active waveguides were performed also by Dixon et al. (2003, 2015, 2018). In some cases, they involved preexisting, reactivated landslides, and in all cases AE (produced by the amplifying medium) were correlated to the rates of internal displacement of the slope along a preexisting shear zone or in a zone that was being formed. We wish to point out that our experiments take a step further, as they demonstrate that significant acoustic activity can be detected even before the occurrence of measurable internal or surface displacements. This means that AE are actual failure precursors—and not merely an amplified proxy of deformation—of first-failure events (i.e., in the absence of preexisting strain localization). This follows from the recognition of the mechanism behind AE and failure in our granular assemblies, namely, the erosion and transport of an internally erodible granular soil fraction. While this might not be the generally dominating cause of slope failures, it can be frequent in fresh coseismic landslide deposits and rock avalanche deposits, which frequently exhibit subsequent rain-induced sudden failures and cause much damage to areas already affected by large catastrophes.

Upscaling from controlled laboratory experiments to full-size applications remains a challenge. However, in a recent contribution, Faillettaz et al. (2016) made a significant advance thanks to the codetection of AEs through a distributed network of sensors that allows to overcome the strong signal attenuation occurring in heterogeneous materials, especially in the presence of pore water and air-water interfaces (Müller et al., 2010). This attenuation might become even stronger when hydrologically triggered failure is approaching, with the soil becoming progressively saturated. In principle, this problem can be solved by a dense network of sensors, but ambiguities would remain on source localization and event size, and installation and management costs could limit its applicability (Dixon et al., 2015). Alternatively, the use of distributed optic fiber networks was also proposed to improve the coverage and sensitiveness of AE acquisition systems (Michlmayr...
et al., 2017). Such technique can be suitable for monitoring slope movements (in principle independently of slope material and failure modes) provided that AEs are sufficiently energetic or that an amplifying medium is introduced (such as a gravel-filled column equipped with a waveguide; Dixon et al., 2003, 2018). Finally, the use of accelerometers to detect the lower-frequency MS, that suffers less attenuation, remains an option, but efforts would be required to discriminate between the signal coming from the deforming slope and the higher background noise, which might hinder the early detection of incipient failures. Moreover, signal preprocessing would be still necessary to identify the frequency content associated to the physical process related to the incipient failure.

A clear physical relation between changes of the values of a monitored parameter and the process that generates such changes is in general beneficial to the effectiveness of warning systems. The better detection capabilities of AE sensors compared to MS sensors (Figures 3o–3u) and the clearer physical meaning of the measured parameter (e.g., Hu, Hicher, et al., 2018; Hu, Scaringi, et al., 2018) can provide a practical advantage for early warning. The codetection method of Faillettaz et al. (2016) seems the best candidate for a full-scale implementation, as it is low cost and requires low computational needs, and thus, the monitoring information can be elaborated in near-real time and timely alarms can be released. However, Faillettaz et al. (2016) have validated it only on small laboratory-scale samples so far. In principle, full-size problems will exhibit not-so-sudden and brittle failures and entail additional material heterogeneities (such as those proper for the deposits of rock avalanches; M. Zhang & McSaveney, 2017). This is expected to make single-sensor or independent-sensor detections unusable and codetection definitely necessary. On the other hand, less brittle failures would imply longer duration of the precursory signals which will be beneficial for warning purposes, but adequate tuning of the sensor network must be performed to catch and interpret these signals correctly.

6. Conclusion

We presented original flume tests on artificial granular slopes prepared at different densities and brought to failure through progressive water saturation, some of which exhibited sudden failure and flow-like landsliding. Previously, we highlighted the role of small, internally erodible soil particles in the propagation of failure and runout of these landslides, which can originate from deposits of coseismic debris, and we suggested possible precursors to identify incipient failures. After investigating the hertz to kilohertz MS, we focused on higher-frequency (kilohertz to megahertz) AEs, generated by particle-scale rearrangements entailing internal erosion and seepage-driven migration of the small-sized soil fraction. We demonstrated that these emissions occur well before the general failure, anticipating detectable pore water pressure spikes, deformations, and significant increases of MS. We showed relations between AEs and relative density of the slope material and creep-like patterns in the cumulated acoustic energy. Even though this study only discusses results from granular slopes in controlled laboratory conditions, we believe that a full-scale implementation of AE-based slope monitoring can improve our early warning capability for some flow-like landslides. It should be noted that, while this work was motivated by the need of understanding and forecasting the behavior of deposits of coseismic debris, the results can be applied to generic granular deposits with gradings and porosities that permit seepage-driven internal erosion.

Acknowledgments

This research was supported by the National Basic Research Program of China: the funds for creative research groups of China (41521002) and the basic research funds (41790433). This research was also supported by the Sichuan funding for young researchers (2016JQ0021). The original data presented in this work can be retrieved from Data Sets S1–S9 available in the Supporting information.

References


