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# Small-scale laboratory experiments of slope collapse under vertical shaking

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Slope collapse can be triggered by earthquake shaking. The collapse should depend on the parameters of shaking, i.e., acceleration, frequency and the duration. There have been many shaking experiments in the field of geotechnical engineering. In the recent years, experiments have also been conducted from the perspective of granular physics (Rubin et al., 2006, Katz and Aharonov, 2006). However there have been very few experiments in which the parameters mentioned above are varied by orders of magnitude. Here we report the results of experiments in which we vary the acceleration and frequency by 2 and 3 orders of magnitude, respectively. We study how the critical acceleration required for the collapse, the collapse velocity and its style depend on these parameters, to better understand the physics of slope collapse.

Experiments were conducted using a small acrylic cell to which a hopper is attached within so that a granular slope with a fixed slope angle forms. We place the cell on the shake table and shake it vertically under a specified acceleration and frequency for 60 seconds. We conduct experiments at frequencies of 10, 100, 1000 and 5000 Hz and acceleration (a) in the range of Gamma = a/g = 0.08-5 where g (m/s^2) is the gravitational acceleration. We record the collapse using a camera and analyze the digital images. The acceleration is measured using an accelerometer.

The initial slope angle was theta = 23.4 $\pm$ 0.5 which is close to the angle of repose (24 deg). From the experiments we find that the collapse style depends strongly not only on acceleration, but also on frequency. We defined 4 regimes : "no collapse", "collapse", "convection" and "jumping". At 100 Hz, the collapse occurs and stops in a short time ($<$10 s) whereas at 1000 Hz the collapse continues throughout the 60 s. We constructed a regime diagram using the slope change rate during the time span of 0-5 s. We find that the critical acceleration for the slope collapse is minimum at around 100 Hz during 0-5 s, but shifts towards 1000 Hz as time elapses. We define two dimensionless numbers, the Shaking strength (S) and Jerk (Yasuda and Sumita, 2014). Here S=(A^2 (2$\pi$f)^2)／ gd ,J=(A(2$\pi$f)^3)／ (g／ (2d／ g)^(1／ 2) ), where A (m) is the shaking amplitude, f (Hz) is the frequency, d (m) is the grain size. The minimum critical acceleration at 100 Hz can be explained by the combined condition of Gamma $>$0.3m, S $>$3.0x10^-5 and J$>$0.3. We next consider the "Jumping" regime. We calculate the height (z') in which the particles jump up from the shake table and find that it becomes larger at high Gamma and low f. Comparing with the experiments, we find that the threshold for "Jumping" regime can be explained by z' $>$10 d.

To summarize, our experiments show that the slope collapse style and velocity depends strongly not only on acceleration but also on frequency and its duration. Characteristic frequency range of the earthquakes is 0.1 – 10 Hz. Our experiments suggest that the difference in the dominant frequency of the earthquakes may cause a variety of collapse styles.The "Jumping" regime may correspond to the "trampoline-effect" which has been proposed to explain the anomalous vertical ground motion in which the upward direction is larger compared to the downward direction (Aoi et al. 2008). In addition, our experiments suggest that there is a frequency band in which the critical acceleration becomes a minimum. This implies that if the dominant frequency of the earthquakes differs, it is possible that the resulting collapse can become larger even under a smaller shaking acceleration. Our experiments suggest that when assessing the possibility of slope collapse, one needs to consider all the possible frequency range caused by the earthquakes.

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