Earth Surface Dynamics
Editor-in-Chief
Dr. Niels Hovius

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"Locating rock slope failures along highways and understanding their physical processes using seismic signals"

Dear Dr. Niels Hovius and Dr. Claire Masteller,

Thanks for handling our manuscript. We hereby submit the revised version of our manuscript for your further consideration. We would like to thank referees for the valuable comments, which we have all taken into account in our revision and certainly helped to clarify the presentation of our work. In the revised manuscript, all of our changes are by tracking. A point-by-point response to all the comments can be found below "Responses to Reviewer's Comments".

Thank you for your time and consideration, we hope very much that our revisions are satisfactory to you.

Yours sincerely,

Jui-Ming Chang, on behalf of all authors

Responses to Reviewer's Comments

Note: Reviewer's comments are all quoted in their entirety and are in *Italics*, while authors' responses are in blue.

Reviewer 1#

The manuscript by Chang et al., is an excellent example of how rock slope failure events can be identified, reported and classified by exploiting regional seismic networks. The paper is well written and structured, analyses carefully carried on, figures appropriated and discussion about pros and cons well explained to the reader. References are also exhaustive. The authors have done a very good job in introducing the framework, explaining into details their procedure, as well as presenting the results of their test cases. I have enjoyed the reading and I believe that the manuscript is already suitable for publication as it is.

No response.

Reviewer 2#

I have had the opportunity to fully review the manuscript "Locating rock slope failure along highways and understanding their physical processes using seismic signals." After reading through this manuscript, I have found it interesting and progressive for its attempted to create a real-time warning system. That said, I think the manuscript needs some work and changes before it can be considered for publication. I noticed that this manuscript has been submitted to GRL in the past and thus may be the reason for some information and in-depth analysis to be missing. This paper will contribute to the overall mass flow community as an example of what can be completed in a specific area. Please address my comments and concerns below.

Major comments:

(1) *ASL does need a priori values, you state they do not on Lines 75,157, etc.. To this extent what are you using for the ASL method for velocity, quality factor, frequency? Likewise, you need to explain how you are estimating "alpha" which contain the a priori values for ASL.*

The basic idea of ASL method is based on the Equation (1), which represents the peak-amplitude at i-th station (A_i) decay with increasing source-to-station distance (r_i). A_0 is the seismic amplitude at the source, α accounts for anelastic attenuation of seismic waves, and n-value controls the amplitude attenuation due to geometric spreading (n=0.5 for surface wave, n=1 for body wave). In this study, we assume surface waves are the dominant seismic wave type induced by the rock slope failures, so the n-value in Equation (1) of 0.5 is used, which is a priori value in ASL only. Finally, there are only two unknown parameters (A_0 and α) in Equation (1). Aforementioned unknown parameters can be inverted directly by fitting the amplitude decay curve with a least-square scheme. We have added text to clarify the above statement. See Lines 161-165.

$$A_i(r) = \frac{A_0}{r_i^n} e^{-\alpha r_i} \quad \text{Equation (1)}$$

$A_i(r)$: the peak-amplitude at i-th station

r_i : source-to-station distance (km)。

A_0 : seismic amplitude at the event source。

α: anelastic attenuation of seismic waves。

n: parameters (n=0.5 for surface wave, n=1 for body wave)

(2) *Source location methods like ASL are influenced by site and path effects, did you try and correct for these? It may reduce some of the large location errors that are shown. If not, there needs to be a statement of why the stations were not corrected.*

We appreciate very much the Reviewer's thoughtful comments. For ASL, several factors such as station geometry, path effects and site amplification may contribute to the location errors. Our results demonstrated that a well-distributed epicentral distance is a crucial factor for the ASL method. We have taken the path effect into account (α is an unknown parameter in our study), and details in discussion can be found in Lines 232-235 and S4 chapter in Supplementary. For the site amplification, previous study has demonstrated that the site amplification could strongly influence the location result (Walsh et al., 2017). At local-scale area, site amplification factors for the specific station can be estimated easily by the ratios of coda amplitudes relative to a reference station (Kumagai et al., 2009). However, the aim of this study is to propose a rapid system to provide information about the timing, location, and moving volume of such events within a short time to highway authority. For the seismic stations along highways, it is difficult to select a reference station, which will be a challenge to comprehensively investigate the site amplification based on the method adopted in Kumagai et al. (2009). In Taiwan, recent studies (Lai et al., 2016; Kuo et al., 2018) about the site amplification for the existed seismic network have been accumulated. Site effect of our station can be corrected and is needed to be done in our future studies. We have modified and added the text to clarify above statement. See Lines 199-207.

Our result presents a location error of maximum 3.19 km for the ten events. In Taiwan, the branches of Directorate General of Highways(DGH) stand along the three provincial highways around every 30 km. Since the GeoLoc system can locate the rock slope failure and provide the location to the DGH rapidly, the true location of the event will be manually checked within a short time. Thus, the location error in our study is still acceptable for the purpose of issuing warning.

(3) *For ASL the frequency range of 1-8 Hz was used for every event? Were any other ranges tested to reduce error, or a sensitivity analysis conducted? Looking at the spectrograms there are events that have peak frequencies or high amplitude content above 8 Hz.*

Thanks for the comment. We understand that the spatial resolution of the high-frequency seismic signals is better than the low-frequency case. However, the relatively poor quality in observed signals for specific frequency content could significantly contribute the large location errors. Thus, a frequency range of filter was selected to result the high signal-to-noise ratio for all stations. See modified text in Lines 133-138 in the revised manuscript.

(4) *Need to explain how you are estimating the location of events by CC. There is only one line of description in the text. There needs to be more.*

We have rephrased and added text to clarify the CC method. See Lines 153-157.

(5) *Check out Kumagai et al., 2013, they link ASL to event magnitude*

Kumagai et al. (2013) found a linear relationship between the seismic magnitude (M_v) and the logarithm of the source amplitude (A_0). M_v can be estimated by the inputs of maximum vertical velocity amplitude (v_{max}) and the source-to-station distance (r). The ASL determines the source location and A_0 simultaneously. In our study, we built two empirical relations: volume and local magnitude (M_L), and seismic amplitude at source (A_0) and volume. The volume was estimated by DGH, not from the seismic signal. However, we can further investigate the relationship between A_0 and local magnitude (M_L) in the future studies, but it is no necessary for the current study.

(6) *Both horizontal and vertical components are used for the location process, but they are computed individually, why not locate the source using all three components together? This has been shown in Walsh et al. 2019 to decrease location uncertainty.*

For the rock slope failures, the characteristics in signals and frequency contents in horizontal and vertical components can be contributed by the different physical processes. In a case of the rock boulder sliding experiment (Hibert et al., 2017), they found the vertical-component signals corresponds to the impact behavior more than the horizontal-component with substantial amplitude. In our study, we expected that the horizontal-component signals probably associated with the sliding action, based on the spectrograms shown in Figures. S1-S4, you can find the Event S2, S3, S5, S6, M2, M3, and N1, whose spectrogram of N-S and E-W (horizontal components) is similar, comparing to the vertical component. That's why we compute the root-mean-square (RMS) amplitudes of the filtered horizontal (N-S and E-W) and vertical waveforms and extract the horizontal and vertical envelope functions from the filtered RMS waveforms for location process.

(7) *There needs to be more testing, more "blind tests" for location and type of event. In Figure 6 you show 5 events from different processes. Does your conclusions about the frequency content and how the event behaves hold up over many events? I like that you state that source-receiver distance plays a large role, but I think there is not enough emphasis on this especially when it comes to comparing different types of events (e.g. Fig 6) at specific frequencies between 1 km and almost 9 km away. I don't know if 6e holds up?*

Comprehensive videos are the robust evidence for the physical process of rock slide and rock topple. The typology of IRM, MS and T is summarized by the known physical process of events and was successfully examined by an event on 12th June 2020. The shape of spectrogram links to the physical process like the landslides with cigar/triangular shape (Chen at al., 2013). Many studies supported that this feature of spectrogram shape can be applied elsewhere and so does the typology of IRM, MS and T. Nevertheless, source-receiver distance of different geological background is a key role to affect the transmission of seismic signal. The seismic signal caused by the Antelao Rockslide with volume around 10^5 m^3 can transmit more than 200 km (Manconi et al., 2016). But the seismic signal generated by Event N1 (the half volume of Antelao Rockslide) cannot be detected when the source-to-station distance is larger than 30 km. The attenuation feature affects the signal decay especially for the high frequency signal and also change the spectrogram features. See Event N1 in Lines 251-255. So, Fig. 6e only work for the source-station distance less than 2.5km. Further, the function of Fig. 6e clarify the physical process for the future application. When detecting the event with location quality A or B and the distance of the best result to the station less than 2.5 km, the spectrogram features are reliable and Fig. 6e can be as additional confirmation.

(8)I think there needs to be a caveat especially in the conclusion stating that these values and inputs that are used in this manuscript are not universal and only apply to this area of Taiwan at close distances, but the methods used can be applied elsewhere, but calibration needs to be conducted.

Modified as suggested. See Lines 334-336.

Line comments:

Line 25: delete first "directly"

Removed as suggested. Line 25.

Line 70: Add citation for lahars (e.g. Kumagai et al., 2009)

Added as suggested. Line 69.

Line 71: change "A" to "at"

Modified as suggested. Line 70.

Line 71: Change or add "main" or "popular" between "two approaches" there are more than two these are just the most used ones for this purpose.

Modified as suggested. Line 70.

Lines 80-82: Where does this come from? You transition from location methods to magnitudes and volumes. Maybe try and rewrite the transition so the reader understands the connection between ASL and volume estimations.

We have moved this part to the next paragraph. See Lines 86-88.

Line 131: Why 180 second time windows?

Based on our experience, the time window length of 180 seconds chose manually is adopted to calculate the signal-to-noise ratio (SNR), which is longer enough to record the entire seismic signals of event. It could be 200, 220 seconds, or larger values. However, the longer time windows possibly cover some onsets of noise signal to mislead the location determination. If you select the different length of time window, the threshold of SNR is needed to adjust.

Line 146: Two stations? You state this elsewhere as well, two stations seems very low to locate a source with any kind of accuracy. Walsh et al. 2017 showed that ASL needs at least 4-5 stations to obtain a reliable result.

We totally agree that only two detected stations cannot offer the location result in accuracy by ASL. In practical, Event S1 and S2 in 2015 was recorded only by the stations from the existed seismic stations operated by the Institute of Earth Sciences, Academia Sinica and the Central Weather Bureau is not good enough for detecting rock slope failures (Lines 103-107). Thus, additional stations have deployed by the author team in 2016 and later (Lines 107-112). Then, the number of available stations rose to 4 for Event S4 and S3 in resulting the reliable location. However, there is still lacking and limitation for the existing seismic network. Like the Event S5 is too small for detecting and the Northeast to Southwest in Sinwulyu catchment inherited high location error due to the imperfect station coverage. We further plan to deploy new stations for the hot pot of rock slop failures to improve the accuracy of location.

Line 150: Need reference for ASL (e.g. Battaglia and Aki, 2003)?

Many references related ASL is cited in the manuscript already.

Line 158: What is the velocity you are using for CC?

A three-dimensional velocity model of Wu et al. (2007) is adopted in this study. See modified text in Line 158.

Line 159: Why a 50 sec time window, seems long for a location method, especially for a moving source.

The time window (50 sec) of the envelope function is for CC to compute the cross-correlation function. It had better to cover the whole process of RSFs. Based on spectrograms of events, the duration of signal ranges from 8.8 to 52 seconds except for the Event M1 and the GeoLoc has been created for the automatic determining location for rock slope failures. So, the time windows as 50 seconds has been assigned which is suitable for any kind of RSFs.

Line 176: Please explain what "N" is defined as better. I had to read several times to understand what "total amount of result location" was.

We have modified text to clarify it. See Lines 176-179.

Line 197: Others have shown station geometry for ASL is important as well, please cite them.

We mentioned the reference of (Walsh et al., 2017) in the revised manuscript. See Line 200.

Line 265: True, but the signals are also influenced by the dynamics and properties of the RSF as well as the medium in which it moves over.

Thanks for the comment. In fact, the spectrogram features such as column, triangular and multiple-pulse shapes quite rely on the source physical processes, providing an opportunity to study a simple typology of the RSF events. Even though the frequency content of signals excited by RSF event would be influenced by the propagation distance, medium property and event magnitude, the shape in spectrogram corresponding to different types of RSF still looks similar. Please also see previous response to "Comment (7)" by the Reviewer 2#.

Line 282: Knowing the location of the source, defies the purpose of a test no? or is this a test on volume and not the whole GeoLoc system?

We have modified and added text to clarify above statement. See Lines 289-290.

Line 293: add space between "theIRM"

Modified as suggestion. See Line 305.

Line 303-311: What about the automatic location estimate of new events?

Please see previous response.

Line 332: delete everything after "activities" and add "around the world"

Modified as suggestion. See Line 346.

Figure 2: Capitalize "n" in both instances. In the text it is an "N"

Modified as suggestion.

Figure 3: State what the seismic amplitude value is in the text and that these are filtered waveforms.

Thanks for the question. The waveforms are the raw data. 1-8 Hz of filtering range was identified based on the spectrograms, depicted by the green dash lines shown in Figure 3. We remove the 1-8 Hz from the figure and put it in the figure caption.

Figure 4: Why are the bottom two events filled differently from all other events? This is not stated in the text, only 1-8 Hz is. Figure 4: What is the red star? Figure 4: I cannot tell where we are in the location figures, you need to put a DEM or map in the background for the reader to get a sense of where these flows are occurring.

An example of filtering range of Event S4 has been shown in Line 133-137. Other events inherit the same way to determine their filtering range which shown in Figs. S1-S4 in supplement material. The modified text has been shown in Line 137-138.

The description of red star has been added in the figure.

We would like to keep the original version of Figure 4. The distribution of relative misfit without background is clear to explain the pros and cons of ASL and CC. To solve the unclear location issue, we revised Figure 1, adding the ten locations of rock slope failures to clarify the location.

Figure 5: Would be nice to have a map or DEM in background for location results

Modified as suggestion. The DEM has been added as the background in Figure 5.

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