Rayleigh waves in seismic signals of rockfalls

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Seismic signals of rockfalls are usually very complex, as they are the result of superimposed arrivals of wave trains generated by successive impacts and have a low signal-to-noise ratio (SNR). Thus, retrieving information from these signals is usually challenging. Our objective was to apply the signal processing method proposed by Meza-Fajardo et al. (2015) in order to isolate Rayleigh waves from the rest of the signals. We expect to retrieve: 1) a simplified output signal as only Rayleigh waves trains are extracted, 2) the azimuth of incoming Rayleigh waves (e.g., information on the rockfall localisation), 3) an output signal with a better SNR than the original signal as the decrease of energy due to geometrical attenuation is proportional to 1/r (with r the distance of propagation) for Rayleigh waves, and is proportional to 1/r² for body waves. Our work confirms the large presence of surface waves for this type of signals (a fact widely accepted in the literature, without ever being really discussed). Future studies will determine whether the use of Rayleigh waves (rather than the entire seismic signal) improves the localization of rockfalls, especially when using a method specific for surface waves (the Fast Marching Method).

1 IDENTIFICATION OF RAYLEIGH WAVES IN ROCKFALL SEISMIC SIGNALS

We used signals of 17 rockfalls recorded by four large band 3-components stations between 2013 and 2015 at the limestone cliff of St Eynard, France. The event volumes were deduced using photogrammetry and range from 1.2 m^3 to 1546 m^3. The distances stations-events range from 0.4 km to 2.9 km. The strong attenuation of the signal with distance, as well as the decrease of SNR with distance are illustrated by a 20m^3 rockfall signal in Figure 1 (left).

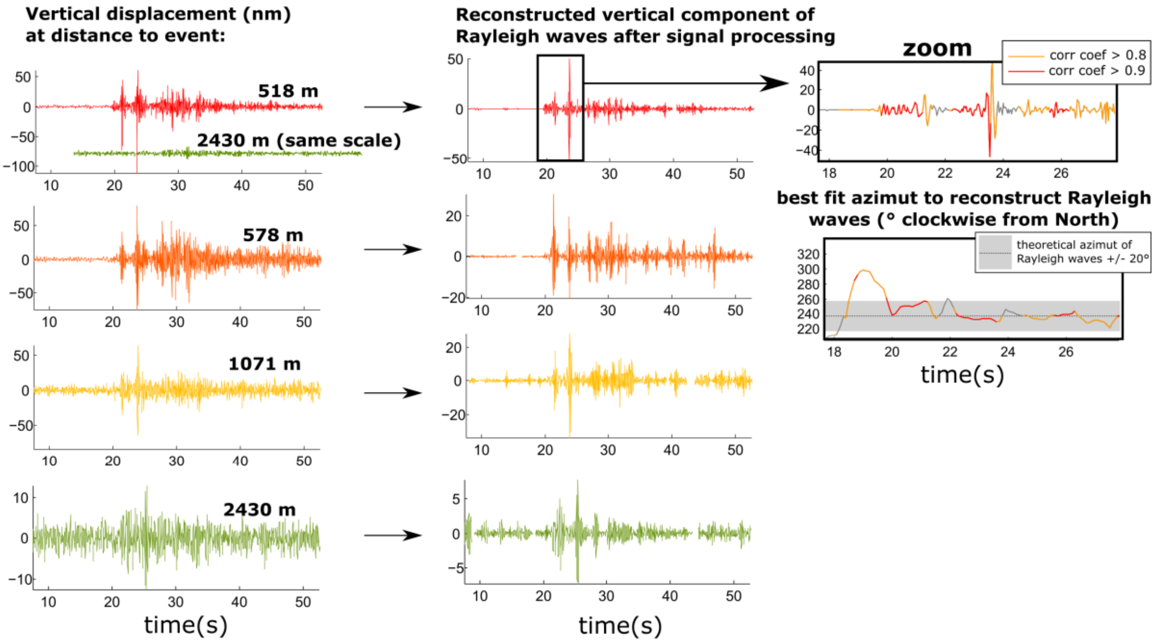

Figure 1: Seismic signals of a 20m^3 rockfall at the limestone cliff of St Eynard (France), recorded by four large band stations at distances from 0.5 to 2.4 km (left). Signals are filtered between 2 and 15 Hz. The furthest is the station; the lowest is the Signal to Noise Ratio (SNR). Signal attenuation is evidenced by the representation of the most distant signal (green) on the same scale as the nearest signal (red). The Rayleigh waves of each signal were reconstructed using shifting windows (middle), showing an increase of the SNR. The zoom of the left plot shows the value of the quality criterion (corr coef) for the signal processing used to reconstruct Rayleigh waves: when this criterion is less than 0.8, we consider that we do not satisfactorily reconstruct Rayleigh waves (hence the presence of holes in the reconstructed signals). The bottom plot shows the best fit azimuth of the reconstructed Rayleigh waves which can be compared to the theoretical azimuth (dotted black line).

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We applied the signal processing method proposed by Meza-Fajardo et al. (2015) in order to isolate Rayleigh waves from the rest of the seismic signals. This method uses the time-frequency signal characteristics deduced from Stockwell transforms (ellipticity, etc.) to construct a time-frequency filter and was originally developed to analyse earthquake signals. Rayleigh waves were extracted using sliding windows of 1.5 s every 0.1 s for a filtered signal between 2 and 15 Hz. The obtained signals show, as expected, an increase of SNR and an overall simplification of the signal (Figure 1 middle).
The particle movement of Rayleigh waves is elliptical, e.g. the signal in the horizontal direction is similar to the signal in the vertical direction by a phase shift of 90°. Therefore, the quality of the filtering process can be verified by estimating the correlation coefficient between these two components. When this coefficient is less than 0.8, we consider that we do not reconstruct an elliptical wave, and therefore, that we do not satisfactorily reconstruct Rayleigh waves. As a result, the obtained signals can present holes (Figure 1 middle). Figure 1 (left) shows the evolution of this quality criterion with time for one signal, together with the best fit azimuth of the reconstructed Rayleigh waves. For this example, the best fit azimuth is more of less very close to the theoretical azimuth (Figure 1 left).

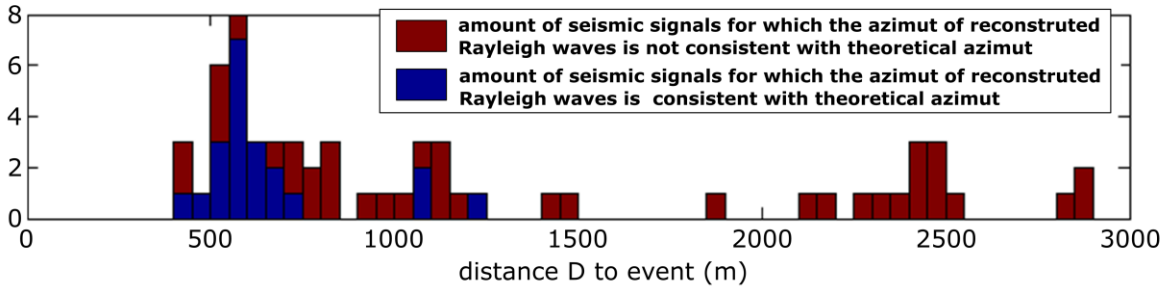

Figure 2: The best fit azimuth of the reconstructed Rayleigh waves was compared to the theoretical azimuth of Rayleigh waves for 17 rockfalls recorded by four large band stations at the limestone cliff of St Eynard, France. The event volumes range from 1.2 m^3 to 1546 m^3 and the distances stations-events range from 0.4 km to 2.9 km.

The best fit azimuth of the reconstructed Rayleigh waves (of the first 2 s of signal) were compared to the theoretical azimuth of Rayleigh waves for the 17 rockfalls (Figure 2). Results show that the best fit azimuth of Rayleigh waves is generally not consistent with the theoretical azimuth, except when: 1) the distance event-station is less than 800 m, 2) the reconstructed signal has a quality criterion greater than or equal to 0.9, 3) the station is located on top of sound rock rather than on scree. The origin of the differences between theoretical azimuth and estimated azimuth has not yet been investigated. At first sight, it seems reasonable to imagine that the wave path is complex for a cliff with scree. Site effects, whether due to topography (cliff) or geology (scree), are likely to influence the propagation azimuth of Rayleigh waves. The greater the distance to the seismic source, the more likely are these effects.

CONCLUSION

The presence of a majority of surface waves in rockfall seismic signals is widely accepted in the literature, without ever being really discussed. This work confirms the large presence of surface waves for this type of signals. For all signals we were able to extract, at least partially, Rayleigh waves (only retrograde waves were obtained). The retrieved signals are simplified (as only Rayleigh waves trains are extracted) and have a better SNR than the original signals. All in all, the proposed method has both advantages and inconvenient to improve the localization of rockfalls with seismic data. On one hand, 1) we obtain a simplified signal with a better SNR, 2) we obtain information on the source-station azimuth when the distance event-station is less than 800 m, 3) we focus the analysis on waves that propagate at slow speeds (a favourable situation to find perceptible arrival-time delays between stations). On the other hand, 1) the proposed method is expensive in computation time and 2) requires knowing *a priori* the position of the source relative to the station at an opening angle of 180 °. In addition, Rayleigh waves are dispersive waves, and it is therefore more difficult to identify the same wave train on different recordings. Further analysis of rockfall seismic signals will be performed using data of a controlled block release experiment that took place in a quarry of Authume (France) in October 2017 (see the paper of Le Roy et al. submitted at RSS 2018 for a description of the experiment).

ACKNOWLEDGEMENTS

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