Locating Flowing Conduits in Karst Using Amplitude-based Passive Seismic Location Method

Haleh Karbala Ali[1] and Christopher J. Bean[2]
[1]Postdoc Researcher, Geophysics Section, School of Cosmic Physics, Dublin Institute for Advanced Studies (DIAS), Dublin, Ireland, haleh@cp.dias.ie
[2]Geophysics Section, School of Cosmic Physics, Dublin Institute for Advanced Studies (DIAS), Dublin, Ireland ,chris.bean@dias.ie

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Abstract

Nearly half of the Ireland is underlain by limestone which has been karstified in most regions. Karst underground systems transport water primarily through cracks or conduits. Locating the flowing conduits and pathways in karst is important in terms of water resource management, groundwater flooding, geotechnical and engineering projects. Understanding flow pathways is particularly important for road and railway construction, so as not to adversely affect hydrological networks, in particular those associated with Turloughs. The aim of this study is to develop methods for directly detecting energetic ground water flow in sub-surface conduits through passive seismic applications, by detecting the small ground vibrations (seismic microtremor) that flowing water in the sub-surface may generate. This is in contrast to the current 'traditional' approach of attempting to actively image the conduits using geophysical and other methods, in order to determine the geometry of flow paths. Imagery of conduits in karst is a very difficult problem and determining if they contain flowing structures is also a very significant challenge using traditional methods, which is the motivation for developing a new approach to the problem. We observed that subterranean flow-related micro-tremor in karst also appears as persistent frequency bands on the spectrograms that varies with time and seismic station location with respect to the conduit. This persistent frequency is different than the soil resonating frequency and relates to the subterranean water flow in the conduits. Application of an Amplitude Location Method (ALM) to the linear profiles clearly delineated the conduit as the source of the micro-tremor in experiments conducted in Ireland. We also discovered a secondary (previously unknown) tributary at one site which demonstrates that this method has the potential to delineate complex subsurface flow structures. We applied the Amplitude Location Method (ALM) to active sledge-hammer shots successfully locating the hammer shots. This validates the approach that we are taking and gives confidence in both the concepts behind and implementation of the methodology.

Introduction

Karst is a landscape with distinctive hydrology and landforms that arise when the underlying rock is soluble. Although karst can develop in evaporate rocks such as gypsum and siliceous rocks such as quartzite, the vast majority of karst landforms are found in carbonate rocks, such as limestones. Karst landscapes may have caves, enclosed depressions, disappearing streams, springs and sinkholes (groundwater Program, Geological Survey Ireland). Nearly half of the Ireland is underlain by limestone which has been karstified in most regions. Locating the flowing conduits and pathways in karst is important in terms of water resource management, groundwater flooding, geotechnical and engineering projects and the biological aspects of Turloughs (seasonal lakes). Karst systems transport underground water through the network of conduits and fractures. The current state of the art is that boreholes (wells) are the primary means of determining the location and dynamics of ground water. However drilling suffers from relatively poor spatial coverage, is financially expensive and can be logistically challenging. In karst, water flows in subsurface fractures and conduits, hence geophysical imagery of these structure (hereafter referred to as: 'structural imagery') has been used to infer possible flow paths. Electrical resistivity, ground penetrating radar and seismic methods can all be employed (Hoover & Asce, 2003). However karst heterogeneity renders it difficult to image leading to uncertainly in the locations of these structures and uncertainty as to whether or not they are in fact 'flowing' (carry water). Source to sink dye tests have also been used to define pathway end points (Benischke, 2021), but the intervening flow path is not constrained. In this project, we move beyond the state of the art and focus on directly 'imaging the seismic source', caused by the water flow itself (hereafter referred to as: 'source imaging'). The core idea is to use the ground micro-vibrations generated by sub-surface water flow to directly detect the flowing water (that is, we do not rely on inferring flow, based on a geophysical image (e.g. resistivity) of the subsurface). Gravity and InSAR can also track spatio-temporal variations caused by subsurface fluids, however InSAR spatial scales of ~100m and temporal resolution of 6-12 days (Tribaldos & Ajo-Franklin, 2021) do not compare with the high spatio-temporal sampling potential of seismic signals (~ 0.2s, < 5m), which can potentially elucidate individual flow structures. Hydrological processes in surface rivers including bed-load transport, turbulent water flow, air bubbles explosion, and propagation of breaking waves induce ground vibrations which can be measured by deploying seismic stations near the river (Larose et al., 2015). The clear evidence of the success of fluvial seismology in detecting surface processes motivated us to apply this idea to track and locate the underground flowing conduits in Irish karst by recording the ground vibrations induced by hydraulic processes in karst systems. Since the source of seismic energy is the natural underground water processes, this approach is a passive seismic method as opposed to the active seismic surveys where human-made sources such as hammer, airgun, dynamite or vibroseis are used to perturb the medium. Again we stress that what differs in our approach is that we aim to directly detect the seismic source (i.e. the micro-tremor caused by the flowing water), rather than creating a sub-surface geophysical 'structural image', which is then interpreted for determining the location of possible fractures or conduits etc (this is the 'traditional approach').

Geological Setting

The cave system under study, called Pollnagran Cave, locates in County Roscommon, Ireland. It is a simple sink to source cave with sinking streams at one end and a spring at the other. The cave is very shallow with some evidence of breakdown of the cave roof. It is a smoothly sloping cave, dipping at about c. 7.3°, with no waterfalls or sudden changes in slope. The glacial material above the cave (sub soils) are between 3 and 5m thick and are classified as Till derived from limestones. The rock is classified as Visean Undifferentiated limestone. This is a very pure, well bedded limestone with chert also seen in cave passages. The main passage is around 600 m in length with average radius of 1 m (Dr. Caoimhe Hickey- Geological Survey Ireland). Figure 1 shows the shapefile of the dived passage of this cave.

Field Experiment

We conducted an experiment between 15-20 December 2020 at Pollnagran Cave, Co. Roscommon, Ireland. We deployed linear profiles consisting of short-period 1Hz seismometers with 2m station spacing. The profiles were deployed perpendicular to the known orientation of the underground conduit.

The profile is then moved forward to record the next line until we covered an areal extent of 50*50 m2 as shown in Figure 2.

Figure 1. Shapefile of the main passage of Pollnagran Cave, Co. Roscommon, Ireland. The shapefile is provided by Geological Survey Ireland.

Alternate profiles were deployed for two hours during the day and overnight, respectively. The first five linear profiles consisted of 25 stations with 4m line spacing while the last 4 profiles consisted of 20 stations with 8m line spacing. We also deployed two broad - band seismometers, 104 1C and 3C 5Hz Smartsolo nodes as both a passive and active (using hammer shots) layout. Here we present the results of the experiment using linear profiles of short-period seismometers.

Figure 2. The coverage of the 50*50 m2 study area using moving linear profiles of 1Hz short-period seismometers.

Method

The pre-processing steps consist of removing the linear trend from data, applying taper and correcting for the instrument response. We computed the spectrogram of the vertical component of the ground motion using sliding windows of 8 second (1600 samples) with 90% overlap. The flow-related signal appears as a persistent frequency band between 10- 20 Hz which varies with time and station location (Figure 3).

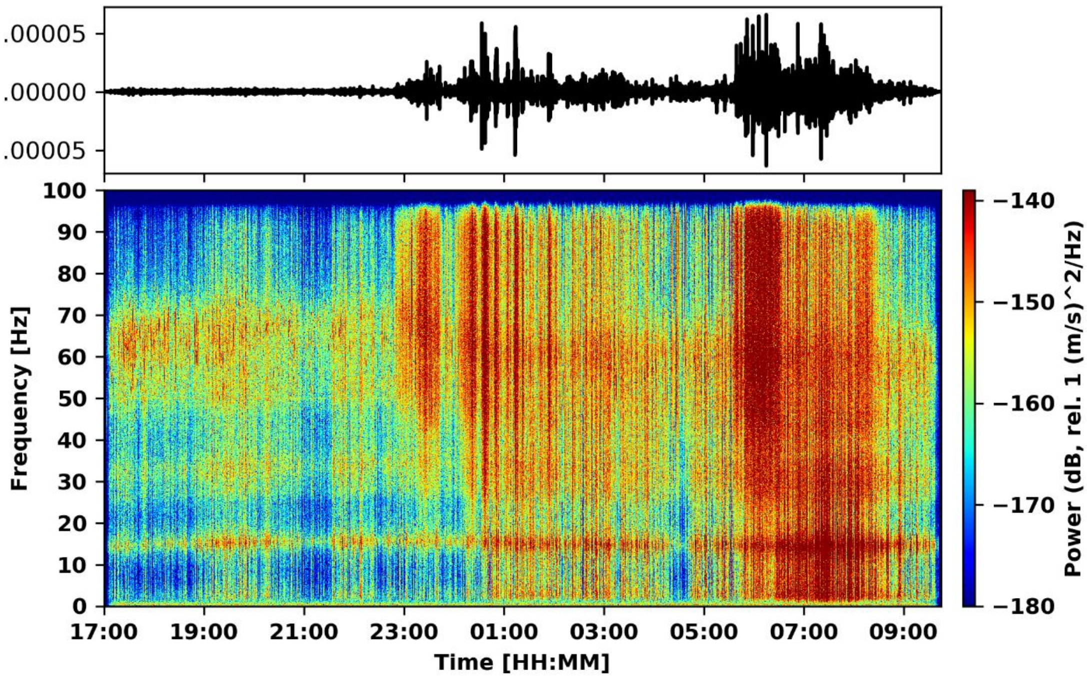

Figure 3. Top: seismic trace and bottom: spectrogram of one of the stations in the first linear profile. The flow-related signal appears as a persistent bandwidth between 10- 20 Hz. As the site was close to a busy road, data is populated with short duration spectrally white arrivals.

The subterranean-induced seismic tremor has no definite onset, so conventional earthquake location methods based on P- and S-wave arrivals cannot be used. To locate the flow-related signal, we apply a method based on seismic amplitudes (Taisne et al., 2011; De Barros et al., 2013). First, we band-pass filter the signal in the frequency range of interest. The surface and/or subterranean flow-induced signal is called tremor (or microtremor) from now on. In the next step, we compute the envelope of the tremor at each station using the Hilbert Transform. To eliminate the effect of transients mainly associated with the cultural noise (passing cars in this location), we median filter the envelopes. The seismic intensity recorded at each station i, with r_i being the distance to the source and I_0 the source intensity is derived using a simple attenuation model as follows, where n can be 0.5 and 1 for surface and body waves, respectively. Here we consider surface wave attenuation.

$$I_i = I_0 \; e^{-Br_i} / r_i^n$$

where B is computed based on frequency f, quality factor Q and shear wave velocity β as follows:

$$B = \pi f / QB$$

To avoid estimating the source intensity I_0, the intensity ratio between different stations is calculated at each time t:

$$\left. I_i \middle/ I_j \right.^{t} = \left(r_j / r_i \right)^{t} \; e^{\left[-B\left(r_i^t - r_j^t\right)\right]}$$

The source locations are found through least-square minimization of the misfit between the ratio of the median filtered envelopes between each station pair in the linear profile and the theoretical intensity

ratio by considering each grid location as a hypothetical source location. Here we located the source every 3600 and 300 second for the odd- and even-numbered profiles, respectively.
In our initial application of the amplitude based location method, we searched for a single (the strongest) source on each profile independently. Figure 4 shows the source locations after applying this method to each individual profile. The colormap is reversed to show the minimized misfit map as the most probable source location. To be able to plot all the misfit maps calculated for different profiles, we divided the rescaled misfit maps by the maximum of the colormap axis.

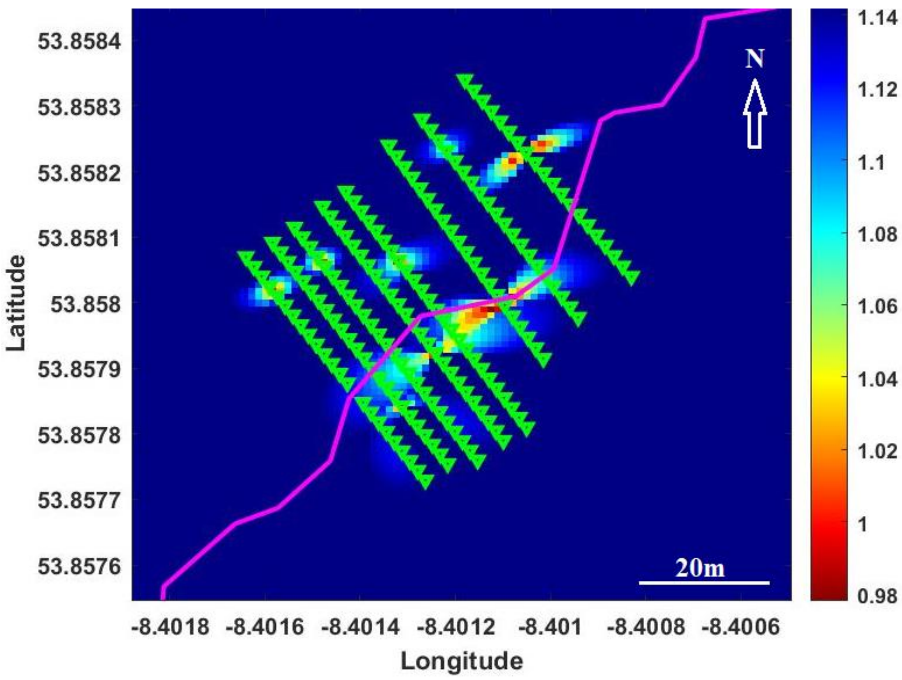

Figure 4. Rescaled misfit maps depict the seismic source locations. The colormap is reversed as the potential source location corresponds to the minimum of the misfit map. There seems to be two underground flow paths; one along the main conduit and the other towards the NW end of the seismic profiles.

As shown in Figure 4 there seems to be two underground flow paths; one along the main conduit and the other to NW the end of seismic profiles. Having unexpectedly discovered that there is more than one flow structure beneath each profile, we modified the Amplitude Location Method (ALM) to search for the two strongest sources, along each profile (searching for more than 2 sources is computationally impractical). Figure 5 depicts the two source locations obtained as the minima of the misfit function color-coded as black and white based on being close to the main dived conduit or to the second newly discovered underground waterway.

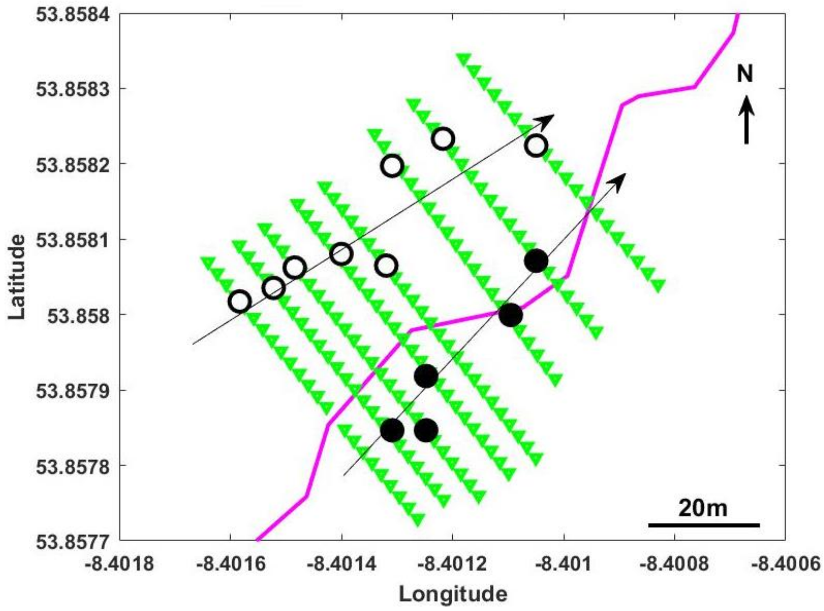

Figure 5. Delineation of two possible underground water courses by adapting the Amplitude Location Method (ALM) assuming a two point source location solution, independently for each profile. The black points are aligned with the main dived pathway (which may itself have some horizontal errors) while the white points demonstrate the secondary discovered waterway.

A field test on the accuracy of our location method

At the end of the passive deployment for each linear profile, we conducted active seismic experiment using a sledge-hammer and plate. We did three shots next to each seismic station with an average shot spacing of 5 seconds. Knowing the hammer shots location and timing, we applied the Amplitude Location Method (ALM) to the seismic data recorded during the shots to test if we can locate the shots with the current station geometry. The successful location of the shots using the Amplitude Location Method (ALM) validates the efficacy of the method in locating the underground water pathways. We applied this method to several stations in different profiles. As an example, we show the location results next to station 8 in linear profile 3. The shots occurred on December 17th 2020 at 09:28:45, 09:28:49 and 09:28:54. We sliced the seismic data between 09:28:44 to 09:28:56. We applied the Amplitude Location Method (ALM) to locate the source every 0.5 seconds. The misfit maps in Figure 6 depict the location of the first, second and third shots next to station 8, located considering surface wave propagation in the Amplitude Location Method (ALM) formula. The white star is the true hammer shot location.

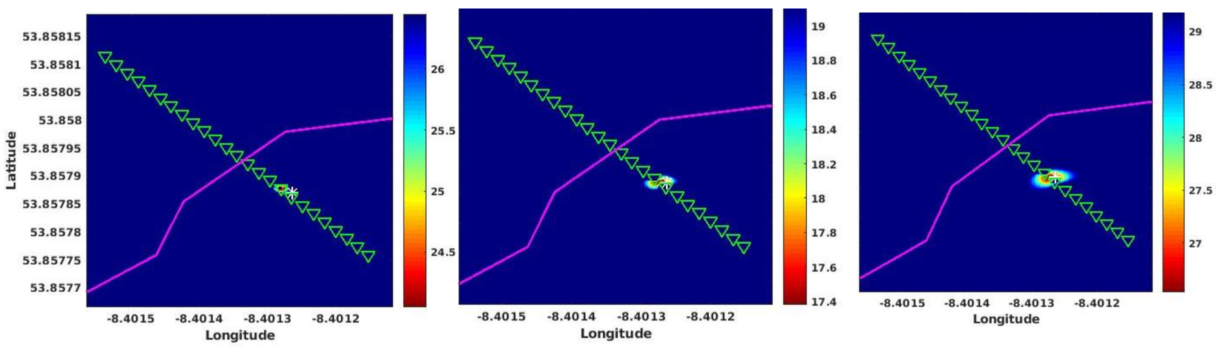

Figure 6. The misfit maps depict the location of the first, second and third shots next to station 8 in the third linear profile based on Amplitude Location Method (ALM). The white star is the true source location.

In the next step, we sliced the seismic data for shots next to station 8 and station 16 of the linear profile 3 and add them together so that the new seismic trace consists solely of active shots next to these two stations. Adding them together simulates a situation where the two sources are active at the same time (just as we have for the proposed two water courses). We then applied the two source solution Amplitude Location Method (ALM) to see if we can detect the two shots. We median filtered the sliced data with a moving 20 seconds windows and located the source every 20 second. Figure 7 shows the location results next to station 8 and 16 with red and blue circles, respectively. The true shot locations are displayed with a black star.

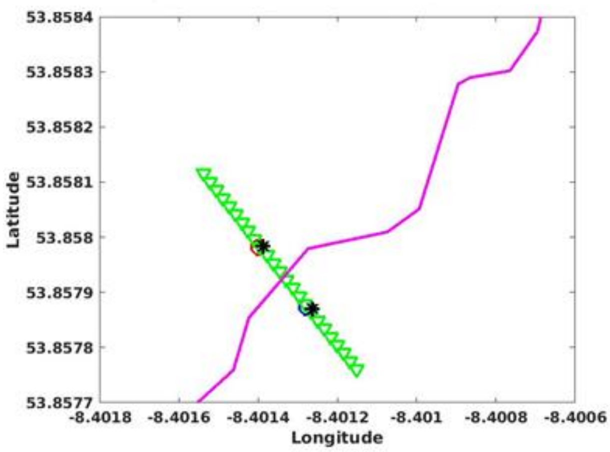

Figure 7. The two source solution Amplitude Location Method (ALM) applied to linear profile 3 to detect shots next to stations 8 and 16. The black stars show the true hammer shots. Blue and red circles display the detected shot locations using ALM, next to stations 8 and 16, respectively.

These tests using active hammer shots demonstrate that Amplitude Location Method (ALM) is capable of locating tremor associated with the subterranean flowing conduit.

Estimating seismic 'site effects' using ambient noise

In sites with overburden or soft soil or fractured rock, the horizontal component of the ground motion (seismic data recorded on the horizontal components of the seismic stations) undergoes amplification in a certain frequency band, while the corresponding vertical ground motion does not significantly get magnified. This is called site effect and the estimation of site predominate frequency and site amplification can be realized through the Fourier amplitude spectrum ratio (HVSR) of horizontal and vertical ground motion (Xu and Wang, 2021). In the next step, we studied the spectral (Fourier amplitude) ratio between horizontal and vertical components of seismic data at several seismic stations. This method demonstrated that the persistent signal we observed on the spectrograms are subterranean-flow induced and differ significantly from the site effect fundamental frequency. Figure 8 shows the HVSR computed for stations 4, 10 and 20 of the first linear profile. We see a large peak in the spectral ratio which differs from what we expect for water flow induced signals. When there are two/multiple peaks in the plot, the first peak is expected to show the fundamental frequency of the site effect and the second is the natural frequency which in this case is the subterranean flow-induced signal (Bard et al., 2008).

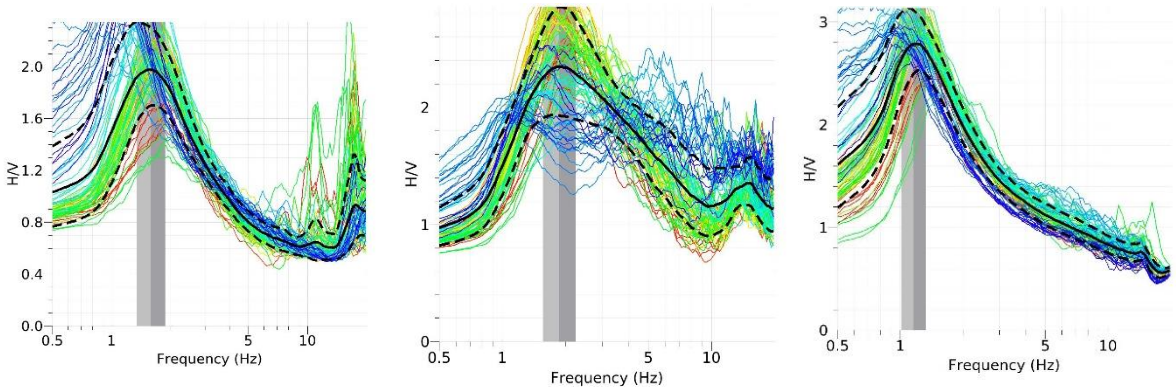

Figure 8. The HVSR plots of a few stations from the first linear profile. The sharp peak around 1.7 Hz is the fundamental site frequency while the second peak around 15 Hz relates to the underground flowing conduit.

Conclusions

In conclusion, we detected a subterranean flow-induced seismic signature as a persistent frequency band in seismic spectrograms. We deployed linear profiles perpendicular to a known 'flowing' sub-surface conduit, based on a previous cave dive. For each linear profile, we applied an Amplitude Location Method (ALM) in the frequency range of interest. We found that the known flow structure is delineated by this methodology, demonstrating that micro-tremor associated with flowing water can be used to detect and track the subterranean water flow paths. In addition, we discovered a second previously un-mapped flow structure at this site (which is consistent with the known overall hydrology, Caoimhe Hickey, *pers Comm*), demonstrating that this methodology has the potential to delineate complex flow networks in the subsurface.

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