Characterizing ground motion from induced seismicity in the context of cultural noises

Technical Report II:

Cultural noise datasets and comparison to induced earthquakes

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Summary

We collect seismic waveforms of various types of cultural, biological noises, tectonic and induced earthquakes, and compare their waveform characteristics, frequency contents and peak ground velocities. Our compilation of cultural noises include ground motion recordings from 1) railway trans, 2) metro trains, 3) snow plows, 4) traffic across bridge, and the biological noise is from fin whale calls in the Lower St. Lawrence Seaway. The earthquake group includes three recent M3-4 tectonic earthquakes near Montreal and three hydraulic fracturing induced earthquakes of M3-4 near Fort St John in northeast BC. The cultural and biological noises have PGVs ranging from 10^{-7} of whale calls to 10^{-2} m/s of Jacques Cartier Bridge vibration. PGVs of earthquakes generally increase with their magnitudes. Induced and tectonic earthquakes of similar magnitudes recorded at comparable source/receiver distances have similar PGVs. A magnitude 3 earthquake results in PGVs $\sim 10^{-4}$ m/s at a station 20-30 km distance, comparable to that generated by a railway/metro train or a snow plow at 20-30 m distance.

Contents

1 Introduction

Seismicity linked to hydraulic fracturing in shale gas exploration in western Canada has increased significantly in the past decade. While most of the earthquakes are of low magnitudes (M<3) and result in negligible felt ground motion, moderate-magnitude events (M3+) can lead to felt reports and societal concerns. To further complicate the matter, event magnitude does not seem to be the deciding factor in terms of ground motion and felt reports. For example, events of similar magnitudes have been detected at different locations and/or different times near HF sites in northeast BC, with only a fraction leading to felts reports, suggesting that other factors, such as event depth, type of faulting, proximity to residential buildings or industrial facilities, may also play a role. Moreover, while the peak ground velocity and acceleration values in the reports provide accurate scientific characterization of the shaking caused by earthquakes, these numbers (e.g., 0.01 cm/s, 0.01g) could appear abstract and hinder the communication of seismic awareness and safety measures to the general public. To our knowledge, no previous work has focused on cross-examining the IS felt reports with a comprehensive earthquake catalog in NE BC to identify possible relations or causal mechanisms. Ground motion measurements of culture noises and natural tectonic earthquakes also exist for various regions, but extra work is necessary to compile into a central database, and to supplement with measurements from designed experiments.

This project is supported by BC Oil and Gas Research and Innovation Society to quantify the relationship between the felt reports and source properties of induced seismicity and to provide a context for the IS ground motion in comparison with cultural noises. There are two research objectives, each defines a project task. The first task is to conduct a systematic review of the IS felt reports in NE BC, cross-examine with a comprehensive seismicity catalog to identify possible relation between the felt reports and earthquake source properties, which resulted in the first technical report (Liu & Bellomo, 2022). The second task is to compile a database of ground motion measurements from a variety of cultural/biological noises, tectonic and induced earthquakes, which can be used to facilitate the communication of IS hazard and safety measures to the general public. In this report, we focus on the findings from Task #2. Here the term "noise" is used in a broad sense as opposed to earthquakes being "signals", and refers to ground vibration due to various types of sources collected in this project. Cultural noise (urban traffic) data collection are conducted by McGill graduate research assistants Justin Chien, Lan Xi Zhu, and PI Yajing Liu. St Lawrence River whale call waveforms are compiled by undergraduate research assistant Eva Goblot. Waveforms and instrument response files are curated by Chien. Figures in this report are prepared and text is written by Liu.

2 Data

In Task #2 of this project, we collect multiple types of seismic waveforms from 1) cultural noises, 2) whale calls, 3) tectonic earthquakes, and 4) induced earthquakes, and compare the recorded ground shaking and frequency content. Cultural noises are recorded with

Origin time	Latitude	Longitude	Depth (km)	Magnitude
2021-05-17 11:03:22	45.825	-73.496	18	3.9 Mn
2022-11-15 02:23:33	45.731	-73.662	9.4	3.5 Mn
2023-01-07 09:59:18	45.478	-73.969	16.9	2.8 Mn

Table 1: Recent magnitudes 3-4 earthquakes near Montreal with epicenters shown in Figure 2. Mn: Nuttli magnitude. Source: Earthquake Canada (`https://earthquakescanada.nrcan.gc.ca/index-en.php`).

Raspberry Shake sensors in the Montreal Area. Whale calls are recorded at the Natural Resources Canada (NRCan) permanent station LESQ on the north shore of the St-Lawrence River. Tectonic earthquakes are selected from recent magnitudes 3-4 events near Montreal, recorded by the Raspberry Shake sensor R74C6 and the NRCan permanent station in Montreal MNTQ. Induced earthquakes include magnitudes 3-4 events in the Kiskatinaw area in northeast British Columbia, recorded by a McGill station MG03 of comparable event-station distances as the tectonic events. All velocity waveform recordings used in this report, with instrument response removed, are archived at `https://liumcgill.wordpress.com/resources/`.

We collected four types of cultural noises, including from railway trains, metro trains on the subway platform, snowplow driving in front of a house, vehicles across the Jacques Cartier Bridge, in the Montreal area recorded by Raspberry Shake sensors (1D and 3D). Raspberry Shake sensors (`https://raspberryshake.org/`) are professional grade, low-cost seismograph and infrasound monitors with an integrated sensor, data logger and portable power supply (Figure 1). The low-weight 'seismograph' can be easily transported and deployed at desirable locations for short-term or long-term recording of ground shaking due to any types of vibration sources, ideal for the purpose of this project. We have utilized recordings at station R74C6 located at the basement of a family house in Notre-Dame-de-Grace of Montreal and a RS3D (purchased through the support of this project) mobile station to various locations in the city (Figure 2). R74C6 only records the vertical component, at a sampling frequency of 100 Hz. The RS3D station records two horizontal and the vertical components at 100 Hz.

Fin whale and blue whale call recordings are from an NRCan station LESQ on the north shore of the St-Lawrence River as shown in Figure 3. Details about the whale call detection using land seismometers can be found in (Plourde & Nedimovic, 2022) and (Goblot et al., 2022).

For tectonic earthquakes, we compiled recordings at both R74C6 and NRCan station MNTQ for three recent earthquakes of magnitudes 3-4 near the Montreal area, as shown in Figure 2 and listed in Table 1.

Finally, for induced earthquakes, we compiled waveforms of the 2018-11-30 M4.5 hydraulic fracturing induced earthquake and its two aftershocks near Fort St John, northeast BC, recorded at station MG03 as shown in Figure 4 and listed in Table 2. More technical details of this induced earthquake sequency can be found in (Peña Castro et al., 2020). The NRCan and MG stations all record at 100 Hz.

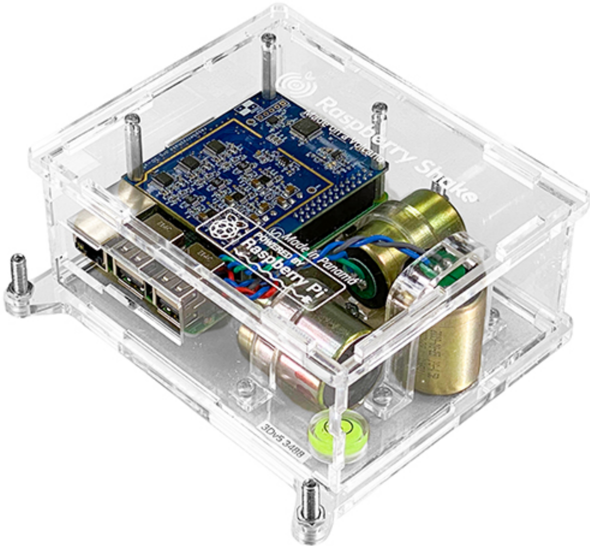

Figure 1: Image of a Rasbperry Shake 3D seismograph. From `https://raspberryshake.org/`

Figure 2: Locations of cultural noise recordings and tectonic earthquakes in/near Montreal. White pin: 1D Raspberry Shake (RS1D) station at a NDG basement (R74C6). Red balloons: mobile deployments in Montreal. A. near rail tracks, B. at McGill metro station platform, C. on the Jacques Cartier Bridge. White dots: epicenters of three recent tectonic earthquakes (details in Table 1).

Figure 3: NRcan station LESQ at (48.3199, -69.3142) on the north shore records whale calls from the St Lawrence River.

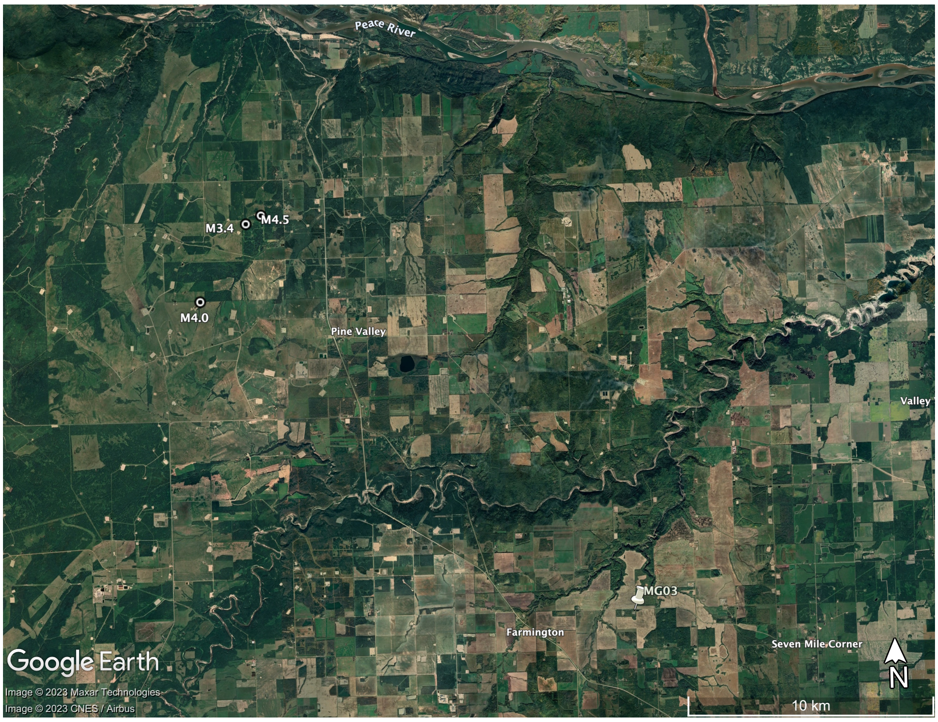

Figure 4: McGill station MG03 at (55.912151, -120.44136) recorded 2018-11-30 M4.5 hydraulic fracturing induced earthquake and its two aftershocks M3.4 and M4.0. White circles: epicenters of the three events.

Origin time	Latitude	Longitude	Depth (km)	Magnitude
2018-11-30 01:27:06	56.06	-120.677	5	4.5 Mw
2018-11-30 02:06:02	56.057	-120.687	5.6	3.4 Ml
2018-11-30 02:15:01	56.029	-120.718	2.2	4.0 Ml

Table 2: Induced earthquakes near Fort St John, BC, with epicenters shown in Figure 4. Mw: moment magnitude. Ml: local magnitude. Source: Earthquake Canada (`https://earthquakescanada.nrcan.gc.ca/index-en.php`).

3 Results

3.1 Cultural noises

3.1.1 Railway trains

We used the Raspberry Shake 3D sensor (RS3D/R2038) to collect ground motion due to railway trains passing near the Vendome station in Montreal. The RS3D sensor was placed at the intersection of Blvd. de Maisonneuve Ouest and Old Orchard Ave. As shown in Figure 5, there are three parallel railways, with approximate distances of 20, 25 and 30 meters to the sensor, respectively. The examples shown in Figure 6 and Table 3 are from trains on each of these railways. Train 1 passed along the nearest railway of $\sim$ 20 m from the sensor; Train 2 along the middle railway $\sim$ 25 m away; and Train 3 included signals of two opposing trains, one on the 25 m and the other on the 30 m railway.

As listed in Table 3, the vertical components are the highest among all the PGV recordings at $\sim 1.5 \times 10^{-4}$ m/s, followed by the north component of 10^{-4} m/s and the east component of $5 - 6 \times 10^{-5}$ m/s. The highest PGV_Z is recorded from the train passing along the nearest railway, although the differences are very small and could be affected by for example other ambient noises.

Figure 6 shows that the train noise energy is widely distributed in the frequency range between 10 and 40 Hz. We can also clearly observe the Doppler effect, illustrated by the rising frequencies as the train approaches the sensor and decreasing frequencies as the train drives away. The time window of peak frequencies coincides with the duration when the highest PGV is recorded in each component. Note that in addition to the train noises that last for 15-20 seconds, there are also short-lived (a few seconds) energy bursts in all the cases, for example, around 10 s, 52 s and 40-42 s on the Z components of *Train 1*, *2* and *3*, respectively. These are from passenger cars driving along Blvd. de Maisonneuve Ouest, which is only 2-3 meters from the sensor (Figure 5).

3.1.2 Metro trains

We also measured ground motion on the platform due to metro trains passing by at the McGill metro station using the RS3D sensor. The distance between the sensor and the metro train is about 5 meters. Figure 7 shows the three components of waveforms and

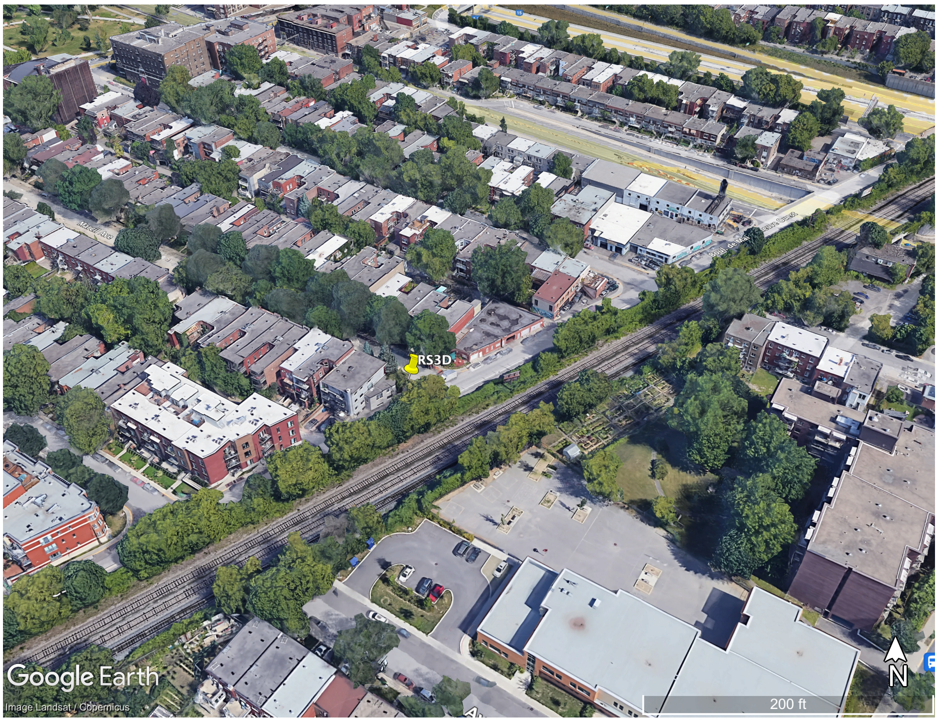

Figure 5: Locations of three rail tracks and the RS3D sensor R2038.

spectrograms of a metro train stopping (around $t = 15$ s) and departing (around $t = 60$ s) the platform, as well as passengers getting on/off the train between ~ 30 and 60 s, most visible on the vertical component (Figure 7c). The maxima PGVs of the three components are comparable on the order of 1-2$\times 10^{-5}$ m/s (Table 3). Most of the energy of the train stop/depart is focused at the high frequency range between $\sim$ 30-50 Hz, with slight indications of the Doppler effect, by contrast to the clear illustration from the railway trains (Figure 6).

3.1.3 Traffic across Jacques Cartier Bridge

We took the RS3D sensor to measure ground motion due to traffic across the Jacques Cartier Bridge in Montreal. The sensor was placed on the bike path, which runs parallel to the freeway as part of the bridge. The source/receiver distance is about 5-10 meters. As shown in Figure 8 and listed in Table 3, this experiment recorded the highest PGVs among all the cultural noise dataset collection, reaching ~ 0.01 m/s on the vertical component, three orders of magnitudes higher than the PGVs recorded by a passing vehicle along Blvd. de Maisonneuve (Figure 6) or a metro train stopping/departing at McGill station at comparable source-to-receiver distances (5-10 m). The reason for the huge PGV increase is not because the vehicles driving across the Jacques Cartier Bridge are of much heavier weights, but because the traffic caused low-frequency, high-amplitude vibration of the bridge itself as any cyclist or pedestrian on the traffic-parallel bike path can clear experience. This high-amplitude vibration is clearly visible on the spectrograms with much higher power densities at low frequencies (generally below 10 Hz, by contrast to above 10 Hz in previous

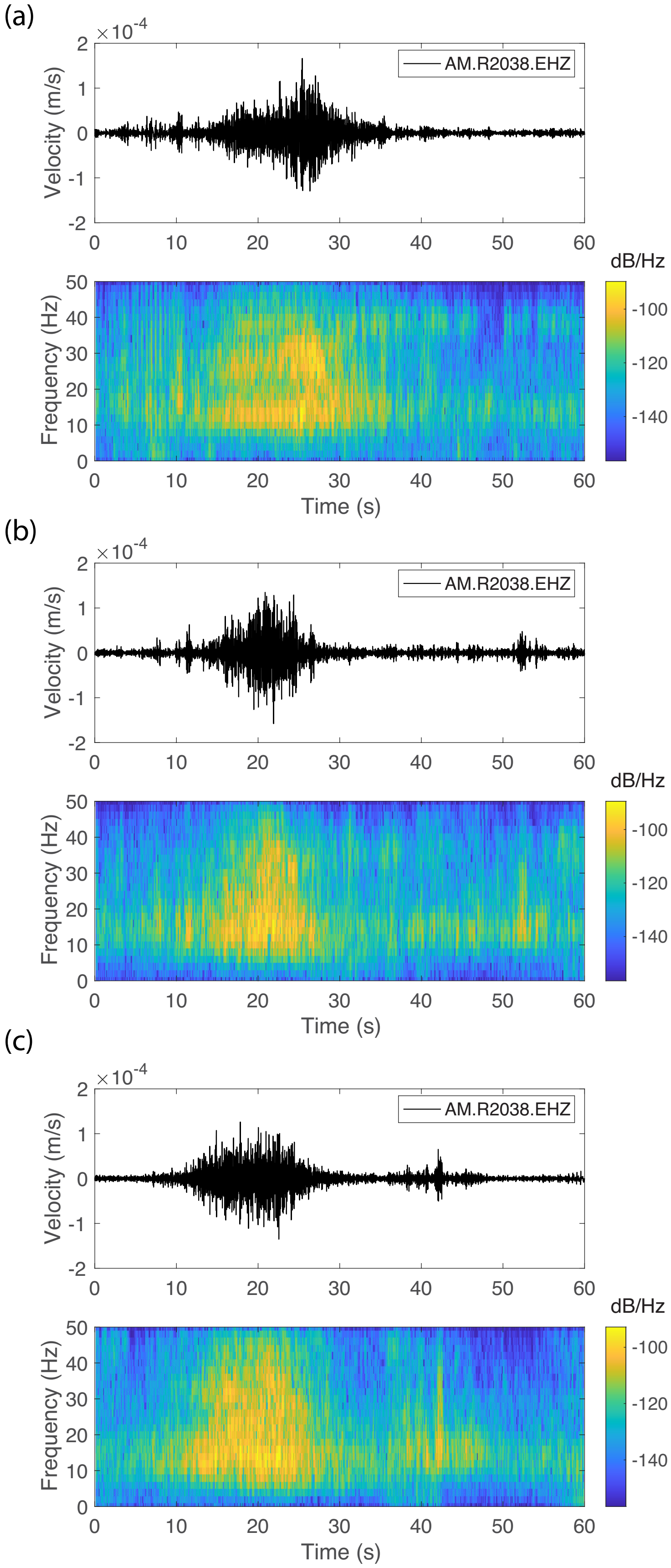

Figure 6: Waveforms and spectrograms of three examples of trains passing by seismograph R2038 (RS3D). (a) Train 1, distance of 20 m. (b) Train 2, distance of 25 m. (c) Train 3, opposing trains of distances 25 and 30 m.

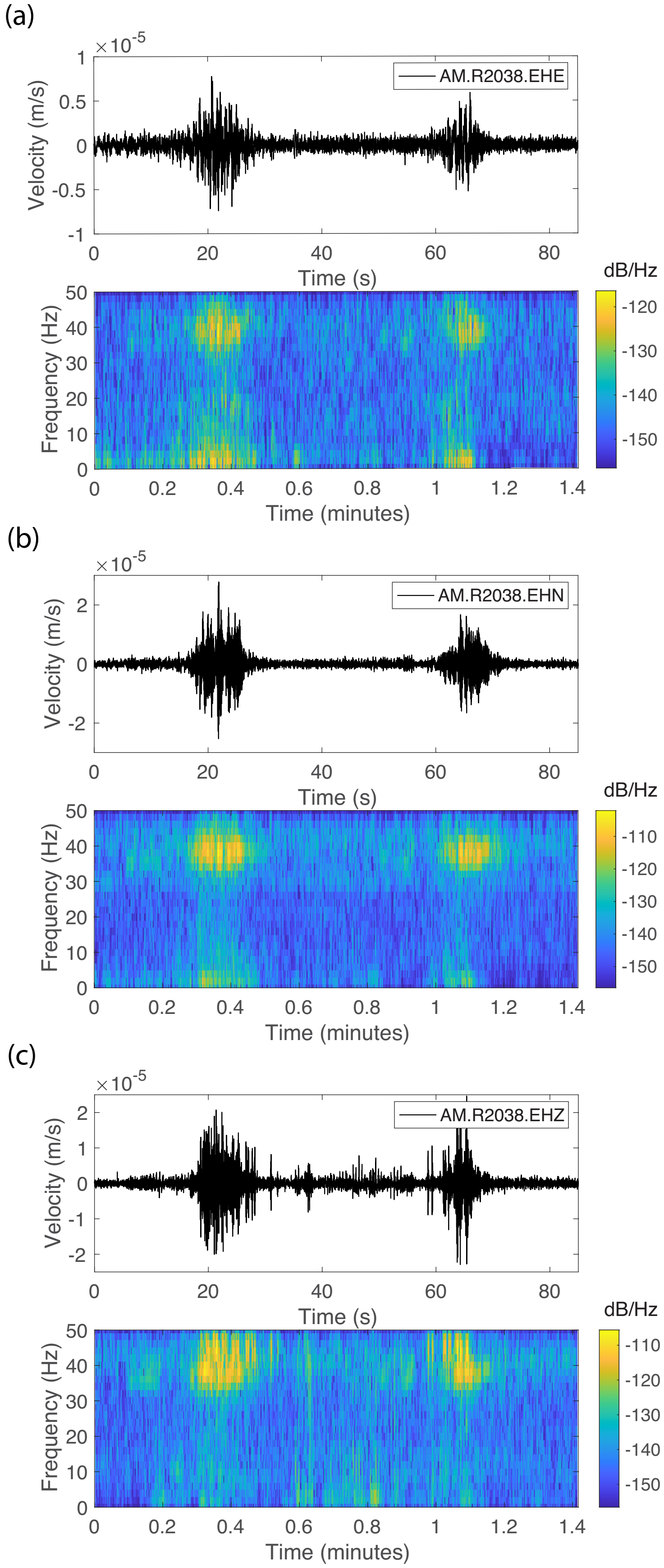

Figure 7: Waveforms and spectrograms of a metro train stopping and departing from the McGill metro station, recorded by R2038 (RS3D). Measurement on platform, $\sim$ 5 m from the train. (a-c) East, north and vertical components, respectively. Note the x-axes for the spectrograms in minutes are aligned with the x-axes in seconds for the waveforms. Total recorded duration is 85 seconds.

cases).

3.1.4 Snow plow

One of the most common comments from Montreal residents description of their earthquake shaking experience is "It was like a snow plow driving by my house". Therefore, here we also collected waveforms recorded by a Raspberry 1D station R74C6 at the basement of a family house in Notre-Dame-de-Grace at southwest of the Montreal Island (Figure 2). The peak ground velocity and spectral content are similar to those generated by a railway train. The spectrogram also illustrates a clear Doppler effect. Energy is focused at frequencies above 10 Hz.

3.1.5 Whale calls

Our group is currently working on a project of using land seismometer recordings along the St Lawrence River (SLR) to detect whale calls and analyze their spatiotemporal variation (Goblot et al., 2022). The whale calls first travel in the water, part of the sound wave energy is refracted into the riverbed and propagates in the basement rock until arrival at the land stations locations on both shores. Here we include two examples of fin whale calls detected at an NRCan station LESQ near the mouth of the Saguenay River on the north shore of the SLR (Figure 3) to show their source characteristics. Figure 10a-b show the waveforms and spectrograms of two one-minute clips at station LESQ (vertical component), each containing multiple fin whale calls. The example in Figure 10 shows clear bursts of energy between $\sim$ 10-30 Hz, each call lasts $\sim$ 1 s and repeats at $\sim$ 10 s intervals. Figure 10c shows a zoom in of one of the calls, where we can see the clear harmonic shape of the sound waves and the gliding frequency pattern (in this case energy moving toward lower frequencies). Figure 10b shows a less clean example, which contains multiple pairs of calls with $\sim$ 3-4 s separation between the two calls in one pair. A zoom-in of one such pair of calls is shown in Figure 10d. This may be an example of two fin whales singing simultaneously. In addition, we also observe high "noise" levels near 45-50 Hz. This could be due to other types of environmental noises such as ships in the SLR. The amplitudes of the PGVs are two to three orders of magnitudes lower than those from trains as shown in previous sections, due the combined effects of the low source amplitude and the long travel distance (several to tens of km).

3.2 Earthquakes

In this section, we summarize the same set of information (waveforms and spectrograms) of natural/tectonic and induced earthquakes. For tectonic earthquakes, we selected three examples of recent magnitudes 3-4 events near the Montreal area, recorded by the Raspberry 1D station R74C6 located in the NDG basement and the NRCan permanent station MNTQ located on the campus of College Jean-de-Brebeuf. For induced earthquakes, we selected three examples of comparable magnitudes (M4.5 mainshock and two aftershocks

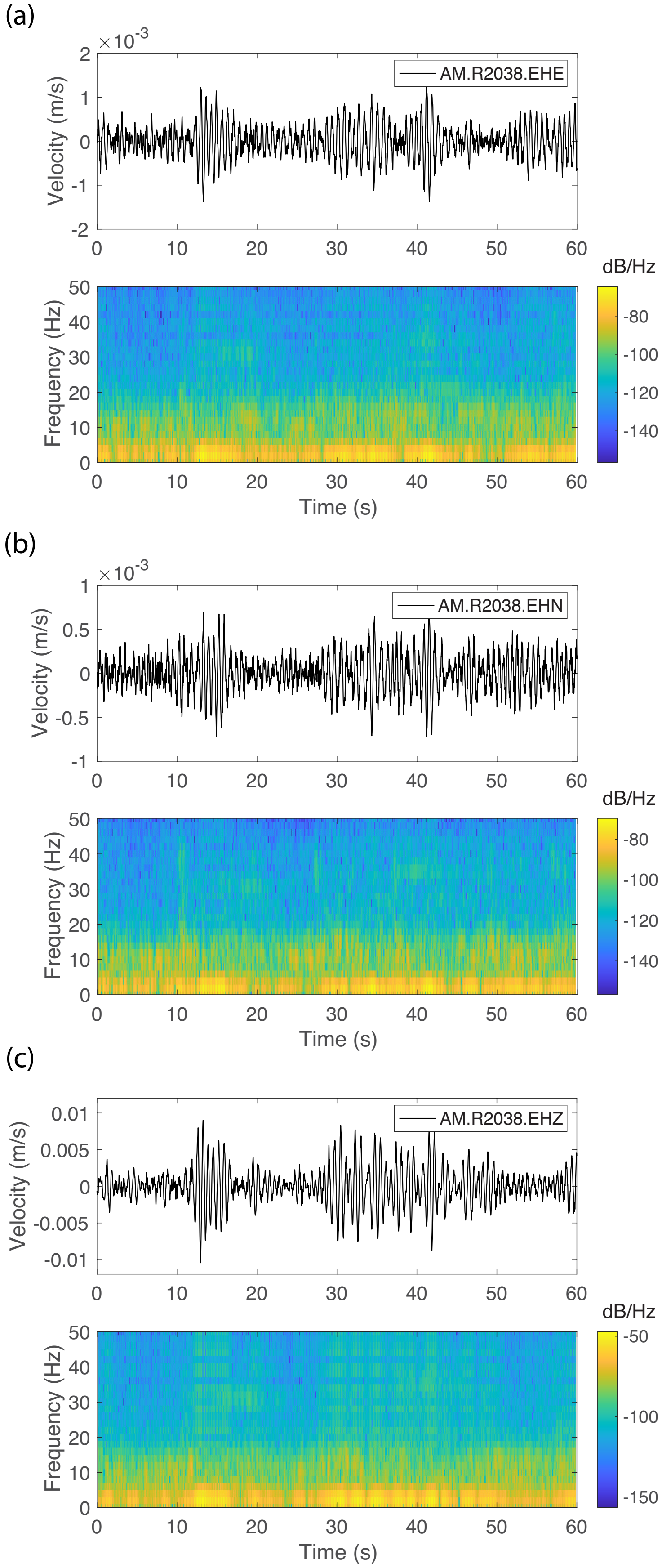

Figure 8: Waveforms and spectrograms of three components recordings by seismograph R2038 (RS3D) of traffic across the Jacques Cartier Bridge, measured at the along-side bike path with source/receiver distance of 5-10 meters. (a-c) East, North and Vertical components, respectively.

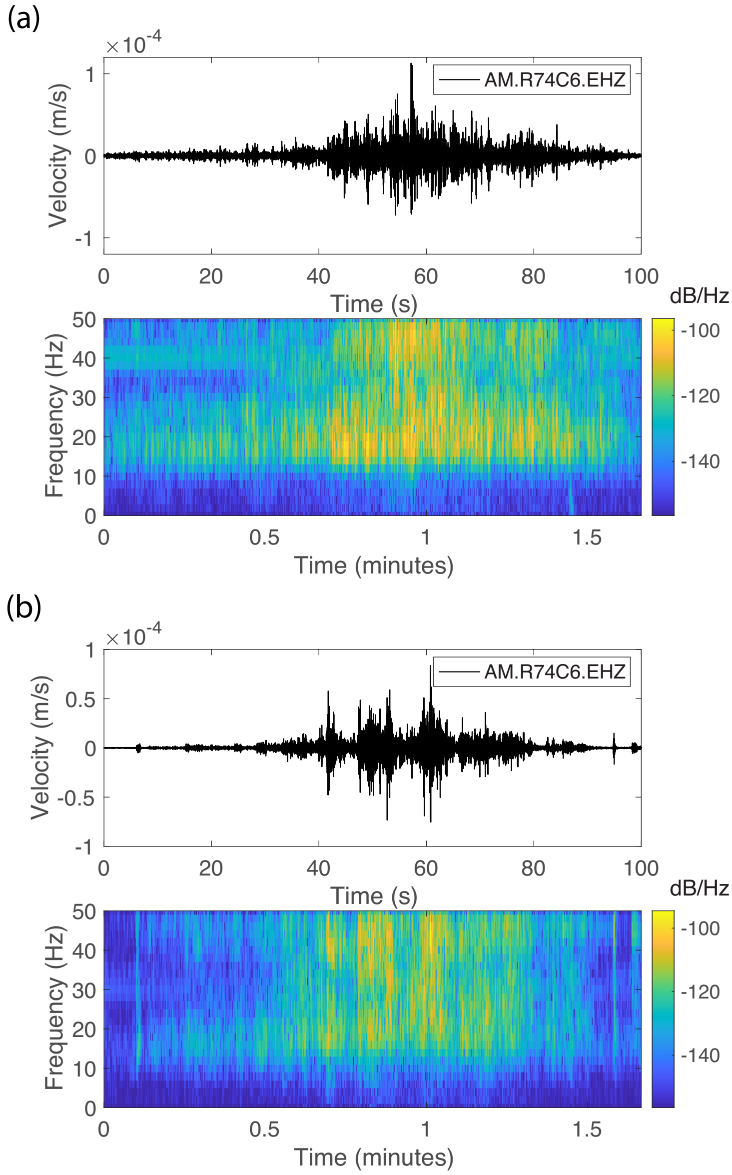

Figure 9: Waveforms and spectrograms of two recordings by seismograph R74C6 (RS1D) of snow plow driving by a family house in NDG, Montreal, in December 2022. Vertical component only. (a) Origin time 2021-12-08 11:42:40, UTC. (b) Origin time 2022-12-21 03:58:30, UTC.

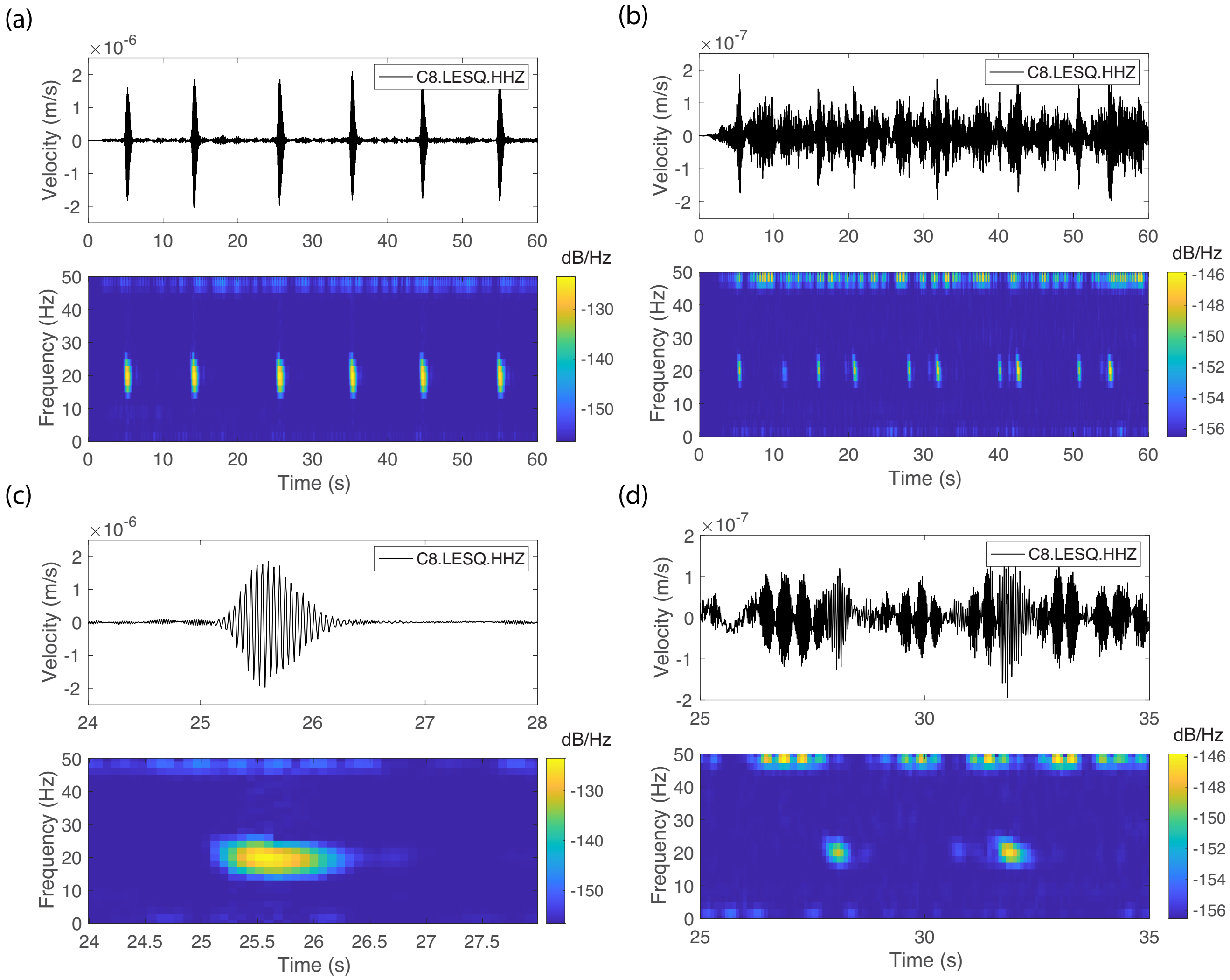

Figure 10: Waveforms and spectrograms of two one-minute recordings of fin whale calls in the St Lawrence River at station LESQ, vertical component only. (a, c) Origin time 2018-09-23 05:11:25, UTC. (b, d) Origin time 2018-09-23 04:42:00, UTC.

M4.0 and M3.4) due to hydraulic fracturing near Fort St John, BC, recorded at a station MG03 of comparable distances as those tectonic earthquake recordings.

3.2.1 Tectonic earthquakes

A few magnitudes 3-4 earthquakes occurred and were widely felt in the Greater Montreal area, including the May 17, 2021, M3.9 near Joliette, QC, and the November 15, 2022, M3.5 near Bois-des-Filion, QC. Figure 11a-b show the waveforms and spectrograms of these two tectonic earthquakes, recorded at the RS1D station R74C6 at $\sim$ 40 and 30 km from earthquake epicenters, respectively. Two very distinctive features of the earthquake waveforms are 1) the clear body wave (P and S-wave) arrival phases, 2) the generally larger amplitudes of S-wave than the P-wave. For a given velocity model, the S-P travel difference is proportional to the station/receiver distance. Therefore, the 2021/5/17 event shows a longer S-P phase offset time ($\sim$ 6 s) than that of the 2021/11/15 event. The body wave energy is mainly concentrated in the 0-20 Hz frequency band. As a cross-check, we also complied waveeform recording of the 2021/11/15 event at the NRCan permanent station in Montreal MNTQ. As shown in Figure 11b and d, the vertical component PGVs are comparable at the two stations, although station R74C6 on the basement floor has overall a higher backgrounod noise level than station MNTQ buried in the ground. Figure 11c shows the same set of information for a M2.8 earthquake on 2023/01/07, located near Dollard-Des-Ormeaux, QC, about 28 km from R74C6. Due to the small magnitude, its PGV is about 1/10 of that of the M3.9 event in 2021. It also has notably a P-wave phase of comparable ampitude to the S-wave phase. Similar feature is observed at the MNTQ station, while another station LONY at Lake Ozonia, NY, USA (about 100 km away) recorded the typical low P-wave hig S-wave amplitudes (`https://www.volcanodiscovery.com/earthquakes/quake-info/7307705/quake-felt-Jan-7-2023-Near-Montreal-Quebec-Canada.html`).

3.2.2 Induced earthquakes

The M4.5 on November 30, 2018 near Fort St John is the second largest hydraulic fracturing induced earthquake in BC (Peña Castro et al., 2020), with widespread felt reports (Liu & Bellomo, 2022). Here we selected the M4.5 mainshock and two aftershocks M4.0 and M3.4 recorded at a McGill station MG03, as examples of comparable magnitudes and source/receiver distances as the tectonic earthquakes presented in the previous section. As shown in Figure 12 and Table 4, because the three events are at approximately the same distance $\sim$ 20 km from the station, the PGVs are proportional to the event magnitudes, with amplitudes consistent with those of the tectonic earthquakes near Montreal. For example, the M3.9 event on 2021-05-17 near Montreal had a PVG$_Z$ of 6-7$\times10^{-4}$ m/s at the R74C6 and MNTQ stations of $\sim$ 40 km; the M4.0 event on 2018-11-30 near Fort St John had a PVG$_Z$ of 7$\times10^{-4}$ m/s at MG03 of $\sim$ 20 km distance. The M3.5 event on 2022-11-15 near Montreal had a PVG$_Z$ of 1.2-1.5$\times10^{-4}$ m/s at the R74C6 and MNTQ stations of $\sim$ 30 km; the M3.4 event on 2018-11-30 near Fort St John had a PVG$_Z$ of 1.4$\times10^{-4}$ m/s at MG03 of $\sim$ 20 km distance. The PGVs of the three induced earthquakes here are consistent with values reported by (Babaie Mahani et al., 2019), which included a broader

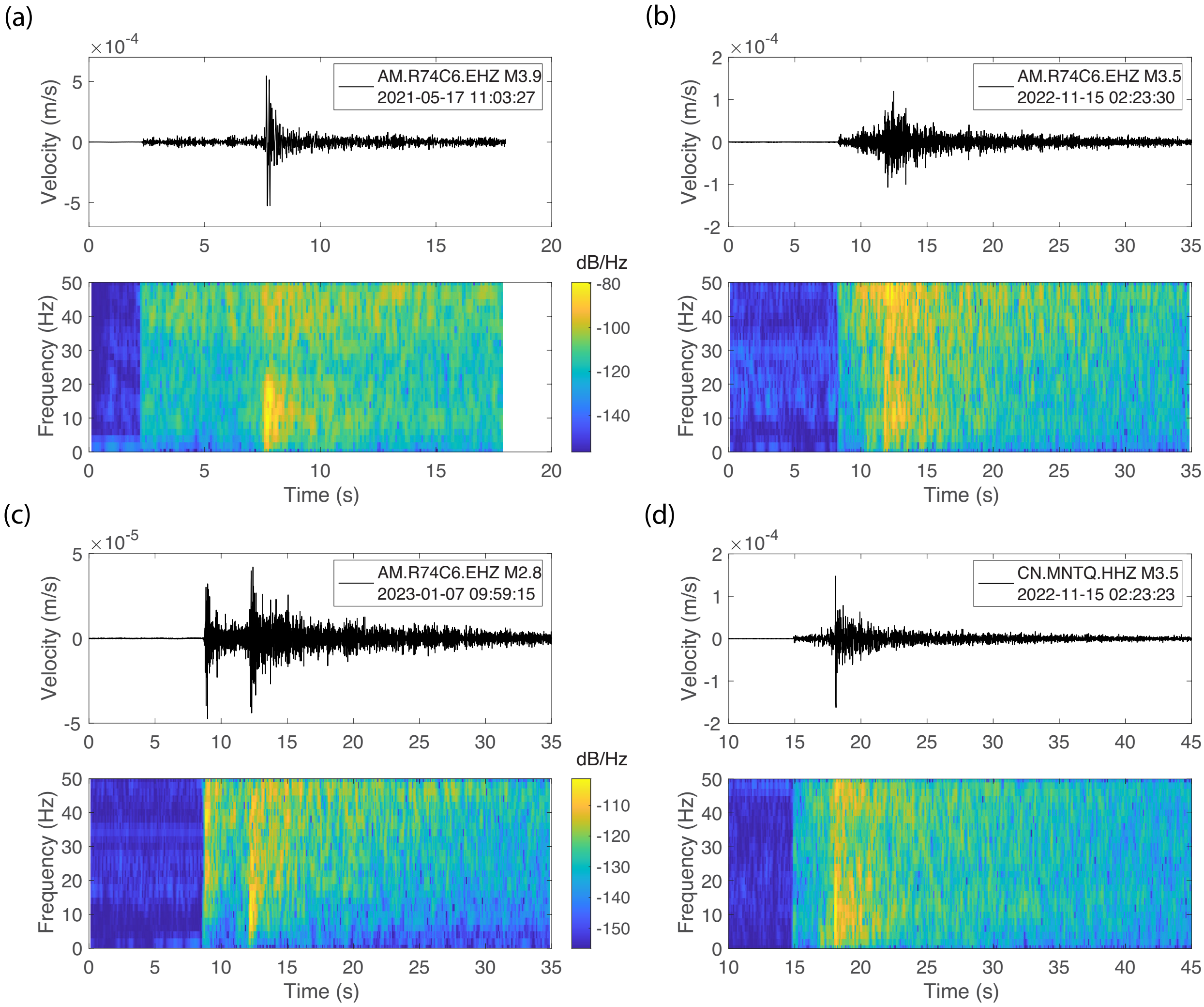

Figure 11: Velocity waveforms and spectrograms of (a-c) 2021-05-17 M3.9, 2022-11-15 M3.5, 2023-01-07 M2.8 earthquake near Montreal, recorded by the RS1D station R74C6 in NDG. (d) 2022-11-15 M3.5 earthquake, recorded at NRCan station MNTQ.

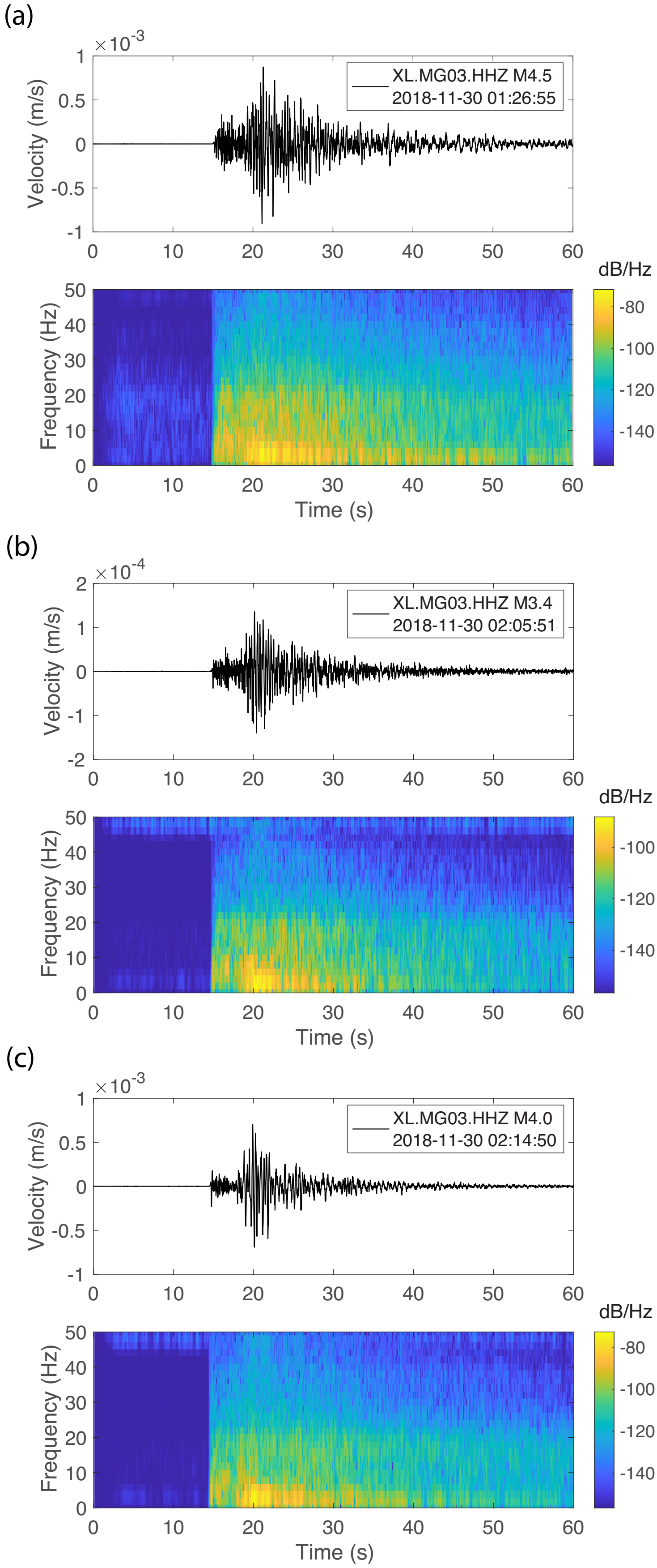

Figure 12: Velocity waveforms and spectrograms of (a) a M4.5 hydraulic fracturing induced earthquake near Fort St John on 2018-11-30, and its (b) M3.4 (c) M4.0 aftershocks on the same day, recorded at station MG03 about 20 km from the earthquakes.

range of hypocentral distances for the same sequence of earthquakes. The spectrograms of the induced earthquakes show lower amplitudes in high-frequency energy compared to the tectonic earthquakes, which may reflect differences in site responses (R74C6 and MNTQ are located in the urban area, MG03 is in the field) and/or the stronger dissipation effect for high-frequency energy in the western Canada sedimentary basin versus the older Canadian Shield.

3.3 PGV summary

Here we summarize the recorded PGV values from various types of cultural/biological noises and earthquakes (Figure 13b) as presented in the previous sections. Three-component PGV values are shown when available. As shown in Figure 13a, the cultural/biological noises vary by nearly five orders of magnitude from $\sim 10^{-7}$ to 10^{-2} m/s. On the lower ends are whale calls recorded by land seismometers along the north shore of the St Lawrence River. On the higher end are the traffic-induced vibration of the Jacques Cartier Bridge recorded on an along-side bike path. The ground shaking due to railway, metro trains and snow plows (all recorded at $\sim$ 5-30 m distances from the sources) are in the intermediate range of 10^{-5} to 10^{-4} m/s. On the other hand, the PGVs from tectonic and induced earthquakes recorded at stations $\sim$ 20-40 km away generally increase with the earthquake magnitude. Specifically, the M2.8 earthquake near Montreal has PGVs around 10^{-4} to 10^{-5} m/s, comparable to those from railway/metro trains and snow plows, and the M4.5 near Fort St John has PGVs around 10^{-3} to 10^{-2} m/s, comparable to those from the traffic-induced Jacques Cartier Bridge vibration.

Item	Traffic	Distance (m)	PGV_E	PGV_N	PGV_Z
1	Train 1	20	5.21×10^{-5}	9.29×10^{-5}	1.66×10^{-4}
2	Train 2	25	6.67×10^{-5}	1.024×10^{-4}	1.58×10^{-4}
3	Train 3	25/30	5.45×10^{-5}	1.023×10^{-4}	1.35×10^{-4}
4	Metro	5	7.76×10^{-6}	2.78×10^{-5}	2.47×10^{-5}
5	Bridge	5-10	0.0014	7.33×10^{-4}	0.0104
6	Snow plow 1	20	N/A	N/A	8.37×10^{-5}
7	Snow plow 2	20	N/A	N/A	1.13×10^{-4}
8	Whale 1	unknown	2.8×10^{-6}	6.91×10^{-7}	2.11×10^{-6}
9	Whale 2	unknown	2.96×10^{-7}	1.84×10^{-7}	2.06×10^{-7}

Table 3: Peak ground velocities of various types of urban traffics (1-7) and whale calls from St-Lawrence River (8-9). Distance is the approximate source/receiver distance, between traffic and the seismograph (RS3D/R2038) for each recorded event. Note that *Train 3* includes signals from two opposing trains passing by at the same time, one on the 30 m railyway, and the other on the 25 m railway. $PGV_E/_N/_Z$ are measured peak ground velocities in east, north and vertical components, respectively. PGV unit: m/s.

Item	Earthquakes	Distance (km)	PGV	PGV_E	PGV_N	PGV_Z
1	2021-05-17 M3.9	40.1	5.46×10^{-4}	3.76×10^{-4}	6.04×10^{-4}	6.35×10^{-4}
2	2022-11-15 M3.5	28.5	1.20×10^{-4}	3.23×10^{-4}	1.62×10^{-4}	1.48×10^{-4}
3	2023-01-07 M2.8	27.2	4.74×10^{-5}	4.83×10^{-5}	5.19×10^{-5}	2.03×10^{-5}
4	2018-11-30 M4.5	22.12	N/A	3.1×10^{-3}	2.2×10^{-3}	9.07×10^{-4}
5	2018-11-30 M3.4	22.23	N/A	3.16×10^{-4}	6.04×10^{-4}	1.40×10^{-4}
6	2018-11-30 M4.0	21.73	N/A	1.40×10^{-3}	2.0×10^{-3}	7.03×10^{-4}

Table 4: Peak ground velocities of (1-3) three tectonic earthquakes near Montreal and (4-6) three induced earthquakes near Fort St John. Distance is epicentral distance between respective earthquake and station pairs. The Montreal earthquakes are recorded at RS1D station R74C6 (PGV vertical component only), and at the NRCan sation MNTQ ($PGV_E/_N/_Z$, east, north and vertical components). The FSJ earthquakes are recorded at station MG03 in 3 components. PGV unit: m/s.

4 Conclusion

In this project, we collected five types of cultural/biological noises and compare their waveform, frequency characteristics and recorded peak ground velocities with those from earthquakes. Specifically, we used Raspberry Shake 1D and 3D sensors and NRCan permanent seismic stations to record ground motion due to 1) railway trains, 2) metro trains, 3) snow plows, 4) traffic across bridge in the Montreal area, and 5) whale calls in the Lower St Lawrence Seaway. In addition, we compiled waveform recordings of three recent tectonic earthquakes near Montreal and compared them with those from hydraulic fracturing induced earthquakes near Fort St John, BC, in the Montney Formation. The tectonic and induced earthquakes have comparable magnitudes ranging from M2.8 to M4.5 and source/receiver distances between 20 and 40 km.

The multiple types of cultural and biological noises exhibit a broad range of PGVs from 10^{-7} to 10^{-2} m/s, with whale calls at the lower end and Jacques Cartier Bridge vibration on the higher end. Ground motion due to passing railway trains, metro trains and snow plows are in the intermediate range of 10^{-5} to 10^{-4} m/s. PGVs of earthquakes in general increase with the earthquake magnitude. A M2.8 event has PGVs comparable to those of trains/snow plows; a M4.5 event has PGVs comparable to the Jacques Cartier Bridge vibration. For tectonic and induced earthquakes of similar magnitudes and source/receiver distances (i.e., the M3.5 near Montreal and the M3.4 near Fort St John), there is no clear distinction in their PGVs, both in the range 10^{-4} to 10^{-3} m/s.

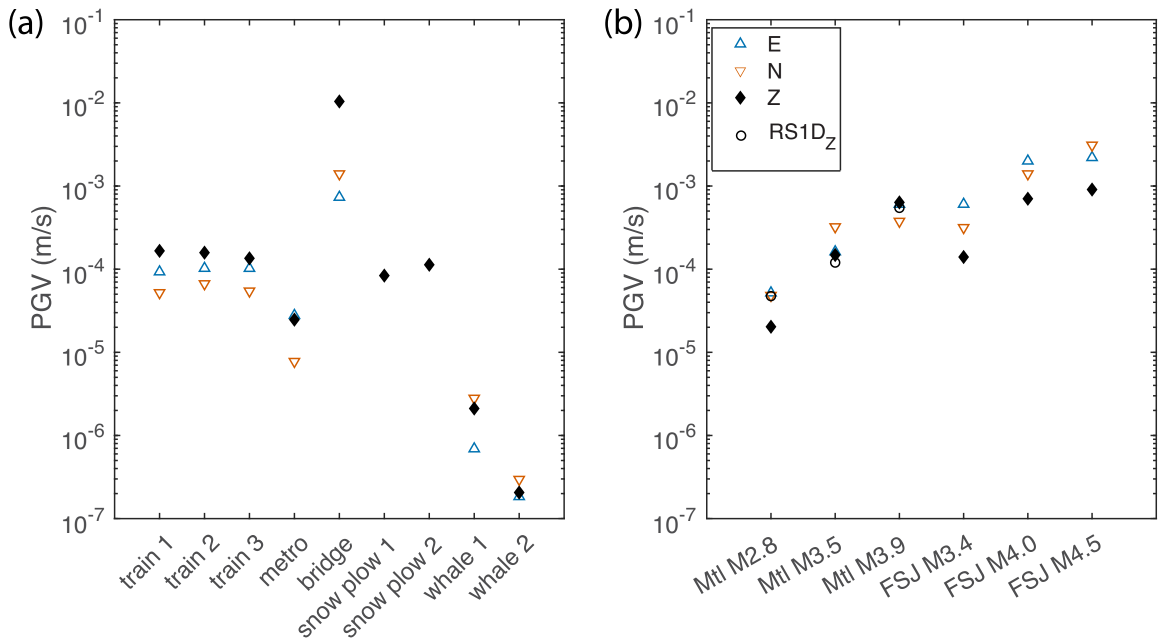

Figure 13: Summary of PGVs from (a) cultural and biological noises, and (b) tectonic and induced earthquakes. Three-component PGVs (E, N, Z) are shown if available. Open circle in (b) are Montreal earthquake PGVs recorded by the RS1D sensor R74C6.

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