Seismic noise recorded by telecommunication fiber optics reveal the impact of COVID-19 measures on human activities

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Abstract

Quantifying the response of human activities to different COVID-19 measures may serve as a potential way to evaluate the effectiveness of the measures and optimize measures. Recent studies reported that seismic noise reduction caused by less human activities due to COVID-19 lockdown had been observed by seismometers. However, it is difficult for current seismic infrastructure in urban cities to characterize spatiotemporal seismic noise during the post-COVID-19 lockdown because of sparse distribution. Here we show key connections between progressive COVID-19 measures and spatiotemporal seismic noise changes recorded by a distributed acoustic sensing (DAS) array deployed in State College, PA. We first show spatiotemporal seismic noise reduction (up to 90%) corresponding to the reduced human activities in different city blocks during the period of stay-at-home. We also show partial noise recovery corresponding to increased road traffics and machines in Phase Yellow/Green. It is interesting to note that non-recovery seismic noise in 0.01-10 Hz suggests the low level of pedestrian movement in Phase Yellow/Green. Despite of a linear correlation between mobility change and seismic noise change, we emphasize that DAS recordings using city-wide fiber optics could provide a way for quantifying the impact of COVID-19 measures on human activities in city blocks.

Introduction

The COVID-19 pandemic has been impacting all aspects of our society, particularly public health and the economy. To reduce the spread of coronavirus, the COVID-19 measures such as working from home, self-isolation, and social distancing were implemented and resulted in a significant disruption to human activities. In the initial stage of the pandemic, the lockdown measures were adopted, resulting in fewer human activities; after the lifting of containment measures, community life and economy restarted, leading to the recovery of human activities. Quantifying the response of human activities to different COVID-19 measures may serve as a potential way to evaluate the effectiveness of the measures and optimize measures in the future (Gupta et al., 2020; Jarvis et al., 2020).

Seismologically, human activities generate vibration noise with the frequency above 1 Hz (anthropogenic noise) (Bonnefoy-Claudet et al., 2006). Several recent studies showed that a significant drop in high-frequency seismic noise levels (1–20 Hz) corresponded to fewer human activities after COVID-19 lockdown in the cities (Xiao et al., 2020; Poli et al., 2020; Lecocq et al., 2020; Yabe et al., 2020). These studies used a limited number of seismic stations in the cities to analyze the reduction of seismic noise attributed to the lockdown. Surprisingly, the recorded seismic data didn't show much distinguishable difference when the level of human activity changed during early isolation before official restrictions were placed and the period after the relaxation of restrictions (Dias et al., 2020; Pulli and Kafka, 2020). One possible reason is that seismic stations have difficulty picking up high-frequency anthropic noise afar due to the city's large spatial extent. During the COVID-19 pandemic, different sectors of the city might respond to the restrictions differently. This highly spatial-varying characteristic of anthropic noise brings the demand for dense seismic arrays in urban areas to provide high-resolution maps of noise variation.

Distributed acoustic sensing (DAS), a recent technology converting optic fibers to dense seismic sensor arrays, could provide high fidelity seismic strain/strain rate measurements at meter-scale spacing (Lindsey et al., 2017; Ajo-Franklin et al., 2019; Zhan et al., 2020; Lindsey and Martin, 2021). DAS has been used for seismic monitoring with tens of kilometers long telecommunication fiber cables (Martin et al., 2018; Lindsey et al., 2019). Recent studies reported new recordings of vehicles, footsteps, and music, highlighting the sensitivity of DAS-equipped fibers in the cities (e.g., Wang et al., 2020; Zhu et al., 2021). Lindsey et al. (2020) reported using DAS with telecommunication fiber to discriminate the traffic noise reduction in different areas (grocery store and hospital) during the COVID-19 pandemic.

Using an underground telecommunication fiber-optics DAS array in State College, PA, USA (Figure 1a), we show significant seismic noise variation from March to June 2020 responding to progressive COVID-19 measures: stay-at-home, Phase Yellow, and Phase Green.

The DAS array

The continuous data we use were collected by the Penn State FORESEE (Fiber-Optics For Environment Sensing) array of underground telecommunication fiber optic cables. The DAS array had a total of 2137 sensors with a 10 m gauge length and 2 m channel spacing. The continuous strain rate measurements are sampled at 500 Hz. We downsampled the data to 250 Hz considering the efficiency in terms of computation and storage. Owing to the unexpected power disruptions, there are no recordings between March 16 – April 15 and May 06 – 26. We analyzed seismic noise variation of 21 weekdays at seven distinct time periods (3 days for each group) from March 3 – June 10, 2020, covering the normal spring semester, spring break, quarantine after the stay-at-home order was issued and the gradual relaxation of the COVID-19 measures.

Our DAS array, which is located at the biggest institution in the town, Penn State University, offers opportunities to explore the social response at city-block scales to Pennsylvania’s progressive lockdown measures that rely on voluntary community action. Penn

State University was closed after spring break on March 18, 2020, and all the residents were required to stay at home, except for essential movements according to the statewide stay-at-home order from April 1, 2020. The social activities started to recover after the official relaxation (designated Phase Yellow/Green) on May 27, 2020.

Spatial distribution of noise variation during COVID-19

We first present the meter-scale spatial variation of seismic noise (RMS strain rate, calculation details in Text S1) across the 5-km DAS array (Figure 1b). Spatially, during the entire period, the seismic RMS noise data were impacted mostly on the main campus, exhibiting the slightest variation in agricultural/sports fields (AG area) and the intermediate variation in the western campus. A significant drop of seismic RMS noise was observed after the implementation of the stay-at-home measure. After Phase Yellow, seismic noise recovered somewhat but was maintained at a relatively low level.

To understand the spatial variation of seismic noise at a 2-meters spacing over the entire array, we calculated the RMS strain rate over 10 hours from 8 am to 6 pm. We repeated the calculation for data on March 5 (spring semester), April 16 (during the stay-at-home order) and June 4 (business reopening) (all Thursdays) and compared with the average daytime RMS strain rate during a week of the spring semester (February 3–7 2020).

Figure 2 shows the seismic noise spatial variation on March 5 (before the pandemic), April 16 (stay-at-home), and June 4 (Phase Green). By analyzing noise in four frequency bands (0.01–1 Hz, 1–10 Hz, 10–50 Hz, and 50–100 Hz), we could distinguish which frequency band of noise was affected by the COVID-19 measures most.

First, the biggest noise variation is detected on the main campus (Figure 2b). The peak noise reduction appears in all frequency bands on April 16 under the stay-at-home order. The largest reduction in the main campus could be up to 90% in the frequency band 1–10 Hz. With the gradual relaxation of the COVID-19 measure policies, the noise level on the main campus increases but remains relatively low (about 60% in 1–10 Hz). Exceptions can be found around Ch 1535–1580, where the noise level is higher during the stay-at-home order, possibly because cars were allowed to enter this area and generated stronger noise than previous pedestrian-only period (restricted before the school closure).

Both AG area and western campus area exhibited less university-related activity. Hence, the noise variation is relatively stable in all frequency bands. The largest noise reduction is in 10–50 Hz, which was likely caused by the decrease in traffic (e.g., school buses and commuter vehicles) due to the COVID-19 lockdown measures. On the western campus, significant noise variation near the end of the array is likely caused by the transition between shutdown (stay-at-home order) and opening (regular semester/Phase Green) of construction-related activities.

We also found that channels around the intersections could detect large noise variation in the frequency band below 50 Hz while noise levels of adjacent channels away from the road remained unchanged. Our fiber array could identify the exact places where traffic noise is dominant, which could help estimate the number of vehicles (Lindsey et al., 2020).

Identification of noise sources associated with human activities

Predominant anthropogenic noise sources vary in different city sectors, among workplaces (Ch 1240–1440), main roads (Ch 850–1110), a residential area (Ch 690–830) and a less populated area (Ch 110–300) (Figure 1b and 2). Characterizing seismic noise from particular sources can help us understand local social interactions with city lockdown measures. Our 5-km-long dense DAS array at 2 m spacing covers plenty of public infrastructures. Hence, we chose specific subarrays and identified noise sources – footstep signals, passing vehicles and industrial noise, by comparing seismic noise variations before and after the COVID-19 restrictions.

To analyze the impact of lockdown measures on footsteps, we selected 1-hour data (local time 10 am–11 am) from a subarray beneath a pedestrian-only path on the main campus for similar days (March 5, April 16, and June 4) (Figure 3). Intuitively, walking footstep signals showed up in the data as linear streaks with a slow moveout (1–2 m/s). On March 5, during the regular semester, the DAS array picked up many walking signals (plenty of data streaks in Figure 3a). Contrarily on April 16, after the stay-at-home order was issued, only a few signals are detected on this path (Figure 3b). In Phase Green (June 4), the footstep signals are almost not recovered despite the easing of some restriction measures. This invariability is confirmed by the average spectrum plot in Figure 3d, showing the absence of peaks at 2 Hz and 4 Hz in both April 16 and June 4 curves, which are considered as the footstep signals (Zhu et al., 2021).

We next analyzed traffic noise recordings (Figures 3e-h) from a subarray beneath Curtin Road, the main road on campus. There is a significant decrease in passing vehicles when comparing data between March 5 and April 16. This is due to the shutdown of the university preventing people from traveling to campus. The bus service was also reduced. On June 4, more linear signals indicate more passing vehicles. The decrease-increase traffic noise pattern is obviously different from the loss-to-flat pattern of pedestrian movement. This trend is also confirmed in the frequency spectrum (Figure 3h): a significant drop of the power spectra between 10 and 50 Hz about 20 dB, then an increase by 5 dB. We interpreted 10–50 Hz as the frequency band of passing vehicles.

In addition, we identified higher frequency noise associated with construction activities. On the western campus, a new parking garage and utility upgrades near the fibers were planned to be constructed from December 17, 2019, to April 20, 2021. Due to the suspension of the industrial activity during the stay-at-home measures, the data on April 15 show no detected events (Figure 3i). After restarting industrial activities since May 7 (Phase Yellow), we observe strong industrial noise on June 1 in Figure 3j. The noise in the frequency band of 10–30 Hz could be identified as noise from construction vehicles and the broadband impulses (10–100 Hz) between 11:09 – 11:10 am were from machinery, which produced short bursts of vibrations.

Temporal noise variation during COVID-19

While significant noise variations across the array are detected, here we show the complete temporal noise variations from March 3 to June 10, 2020. Figure 4 shows the time-lapse noise changes recorded by Ch 981 located beneath Curtin Road on the main campus (Ch 204 in Figure S1 and Ch 1491 in Figure S2). As a comparison, seismic noise changes are plotted against the Google mobility data from workplaces and transport across the county (details in Text S2). Although detailed mobility data near the fiber are unavailable, a general validation could be conducted.

First, we can see that noise experienced a slight decrease (up to 10%) in the spring break compared to the regular spring semester in the low-frequency band (0.01–10 Hz). This decrease (<10 Hz) is attributed to the least school activities during spring break (i.e., many students left school and there were few school activities). In 10–50 Hz, the noise changes in both Ch 981 (Figure 4) and Ch 1491 (Figure S2c) remain flat before the stay-at-home order, while the change in Ch 204 (Figure S1) decreases. During spring break, the quiet roads (Ch 204) are more likely to have reduced vehicle traffic while the main road on campus (Ch 981 and 1491) might remain busy (e.g., citizens driving across the campus and regular bus services). In the high-frequency range (50–100 Hz), the noise changes only decrease in channel 1491 (Figure S2d), which is likely caused by stopping machinery noise (from a construction site near Ch 1491).

After the university closure on March 18, a distinct drop (up to 60% daily average) of noise levels falls to the lowest level in the whole period of the stay-at-home phase (Figures 2 and S1 and S2). Moreover, this universal noise reduction in all frequency bands (0.01–100 Hz) reflects the quieter period and the huge reduction of noise sources due to the stay-at-home order. We inferred that the campus had very few human activities.

After Phase Yellow on May 27, the noise level (0.01–10 Hz) still stays flat at the lowest level (50%~60% reduction) until Phase Green. This feature implies that residents continued to follow the stay-at-home guidelines (e.g., working at home). Interestingly, the noise level (10–100 Hz) increases gradually, which is consistent with the mobility data (transport), suggesting the recovery of road traffics and industrial activities (e.g., shopping and construction business). After Phase Green, the noise in all frequency bands gradually increases by a few percentages (1–10 Hz) to 20% (0.01-1 Hz).

We calculated the root mean square error (RMSE) between Google mobility data from two categories and noise changes in four frequency bands discussed above (Figure 4). A smaller RMSE represents a better correlation with the mobility data in a particular category. We interpret noise sources in the frequency bands of 0.01–1, 1–10, 10–50, 50–100 Hz as school activities mixed with bedrock loading of vehicles (Lindsey et al., 2020); school activities; traffic signals; traffic signals mixed with industrial activities, respectively.

Comparison to mobility data

To generalize the relationship between seismic noise and mobility data, we calculated an averaged seismic noise change for a single day by first averaging 24 hours noise changes for each channel and then averaging them across all channels. Figure 5 shows a crossplot between the noise data and Google mobility data. The noise reduction in the frequency band of 1–10 Hz is compared with the workplace mobility data, while the 10–50 Hz noise level reduction is compared with transport mobility data. The good linear correlation between mobility change and changes of seismic noise level allows us to relate variation of seismic noise level and mobility changes as,

$$M_{TL} = 1.49 N_{TL}$$

where M_{TL} is time-lapse mobility change and N_{TL} is time-lapse noise change. This linearity implies that the seismic noise variation (1–50 Hz) is linearly proportional to the amount of human activities, including foot traffic and road traffic.

Discussion and Conclusions

While a general noise reduction was discovered in many cities by previous studies (Xiao et al., 2020; Poli et al., 2020; Lecocq et al., 2020; Dias et al., 2020; Yabe et al., 2020), our results reveal many new and detailed features of seismic noise caused by progressive COVID-19 measures.

First, we find the seismic noise reduction in broad frequency bands (0.01–100 Hz) caused by decreased human activities during the period of stay-at-home (March-April 2020). After Phase Yellow (May-June 2020), the seismic noise recovers slightly in high-frequency bands (10–100 Hz), while the noise in 1–10 Hz shows no recovery until late Phase Green. We interpret that after the relaxation of restrictions, residents voluntarily followed the stay-at-home guidelines (i.e., less pedestrian movement) while road traffic and industrial activities started to recover. These results show that the dense DAS array in urban areas could sense slight changes due to the gradual lifting of restrictions since the end of May. Noise changes caused by particular human activities (e.g. pedestrian movements and industrial activities) can also be identified in different frequency bands. The sensitivity of the DAS array indicates the possibility of using seismic noise variation from telecom DAS in the city-block scale to evaluate local response to social restrictions.

Second, seismic noise in the low frequency band (0.01–1 Hz, where anthropogenic noise is weaker) is also impacted by the COVID-19 measures, which was not reported in previous studies using seismic networks (Xiao et al., 2020; Lecoq et al., 2020; Poli et al., 2020). Lindsey et al. (2020) observed a reduction in the very-low-frequency seismic noise (0.01–1 Hz) using fiber sensors along a major road in Stanford, CA, during the COVID-19 pandemic. This reduction is likely to be the geodetic response of the roadbed to decreased vehicle loading (Lindsey et al., 2020; Jousset et al., 2018), providing an additional constraint to quantify the number of passing vehicles using dense seismic noise data.

Third, the meter scale human activity variation is hard to be obtained from either sparse seismic stations or mobility data due to incomplete data acquisition, location accuracy, and privacy issues. In contrast, DAS could provide a high spatial resolution map of seismic noise variation, which can distinguish different human activity variation patterns between the main campus and agricultural area, and further identify dominant noise sources on different streets within each area. For instance, the significant noise reduction, almost 90% in the frequency band 1-50 Hz, on the main campus is attributed to few local concentrated human activities (including footsteps and road traffic) due to the required stay-at-home order in State College PA. Seismic noise in less busy areas (AG areas) remains relatively stable. In the local noise reduction zone (main campus), we could distinguish footsteps, single passing vehicles, and high-frequency industrial noise associated with construction activities (Figure 3). The spatial noise variation provides detailed information on population mobility dynamic in urban areas, demonstrating that the lockdown measurements have a significant impact on certain populated areas (e.g., universities) during the COVID-19 pandemic.

Finally, a linear correlation between mobility change and seismic noise change implies that high-resolution DAS seismic noise data could further serve as an additional and innovative approach for evaluating the impact of the COVID-19 measures in populated areas related to industrial, educational, and other activities. DAS data contain non-personalized information and enable urban monitoring use patterns, which protects the privacy of individuals compared to cell phone location-tracking data (Lindsey and Martin, 2021). This suggests the benefits of using city infrastructure fiber-optic cables over the mobility data to monitor and quantify human activity in a city (e.g., estimation of people's movement and the number of vehicles) with high spatiotemporal resolution.

In summary, our results show key connections between the progressive COVID-19 measures and spatiotemporal seismic noise changes using a dense fiber array at the city scale, which helps estimate whether and how communities respond to county-level policies. Our research shows that seismic noise recorded by infrastructure DAS fiber networks could potentially help policymakers to evaluate the compliance of the population following state-mandated mobility restrictions, which in-turn could optimize the restriction policies in the future pandemic. Looking forward, fiber-optic arrays using existing telecommunication fiber networks make seismic monitoring more cost-effective and practical than other types of seismic sensors in urban areas.

Data and Resources

The DAS data used in this study are collected by the Penn State FORESEE array of underground telecommunication fiber optic cables. Calculated seismic noise level and raw DAS data used for plotting figures in this paper are available for download at https://doi.org/10.5281/zenodo.4072484. The mobility data are released by Google at https://www.google.com/covid19/mobility/ (last accessed: 25 September 2020). We used ArcGIS Pro to make Figure 1a. Supplemental Material for this article includes: 1) methods about the calculation of the RMS noise changes; 2) a description of Mobility Data we used; 3) two figures of temporal noise level changes at Ch 204 and 1491.

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Figures

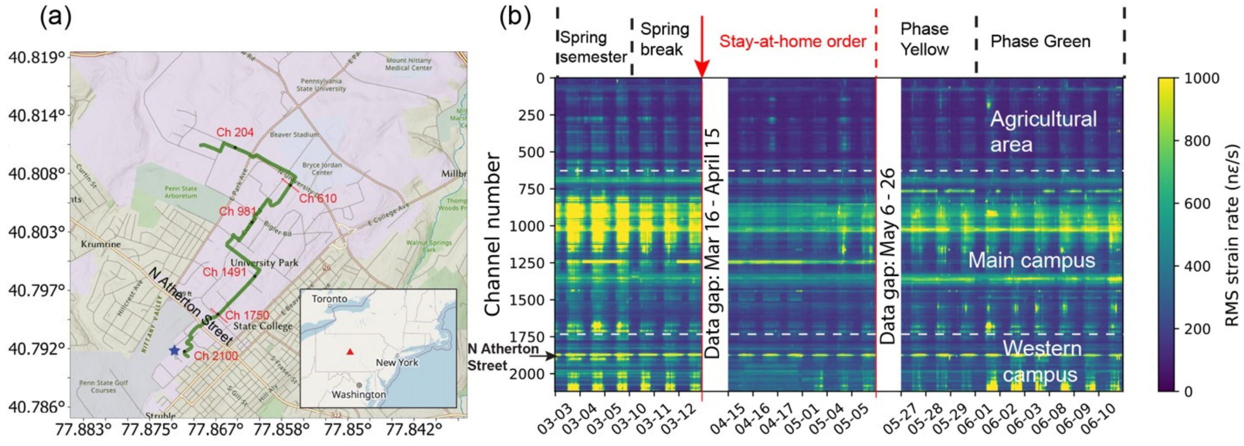

Figure 1. (a) DAS map. Dark fiber (Green line) is located beneath Penn State University campus in State College, Pennsylvania (inset, red triangle). Selected channels are indicated for referencing sensors' location. The blue star indicates the construction site. The red dashed lines divide the campus into three sections. (b) Temporal variations of seismic noise across the DAS channels. The timeline of local conditions is shown above. Note that dates are not continuous and the white space indicates the data gaps due to unexpected power interruptions. Red line marks the abrupt noise change during the implementation of the stay-at-home order. A Clear diurnal pattern shows that signals are mainly from human activities in the daytime.

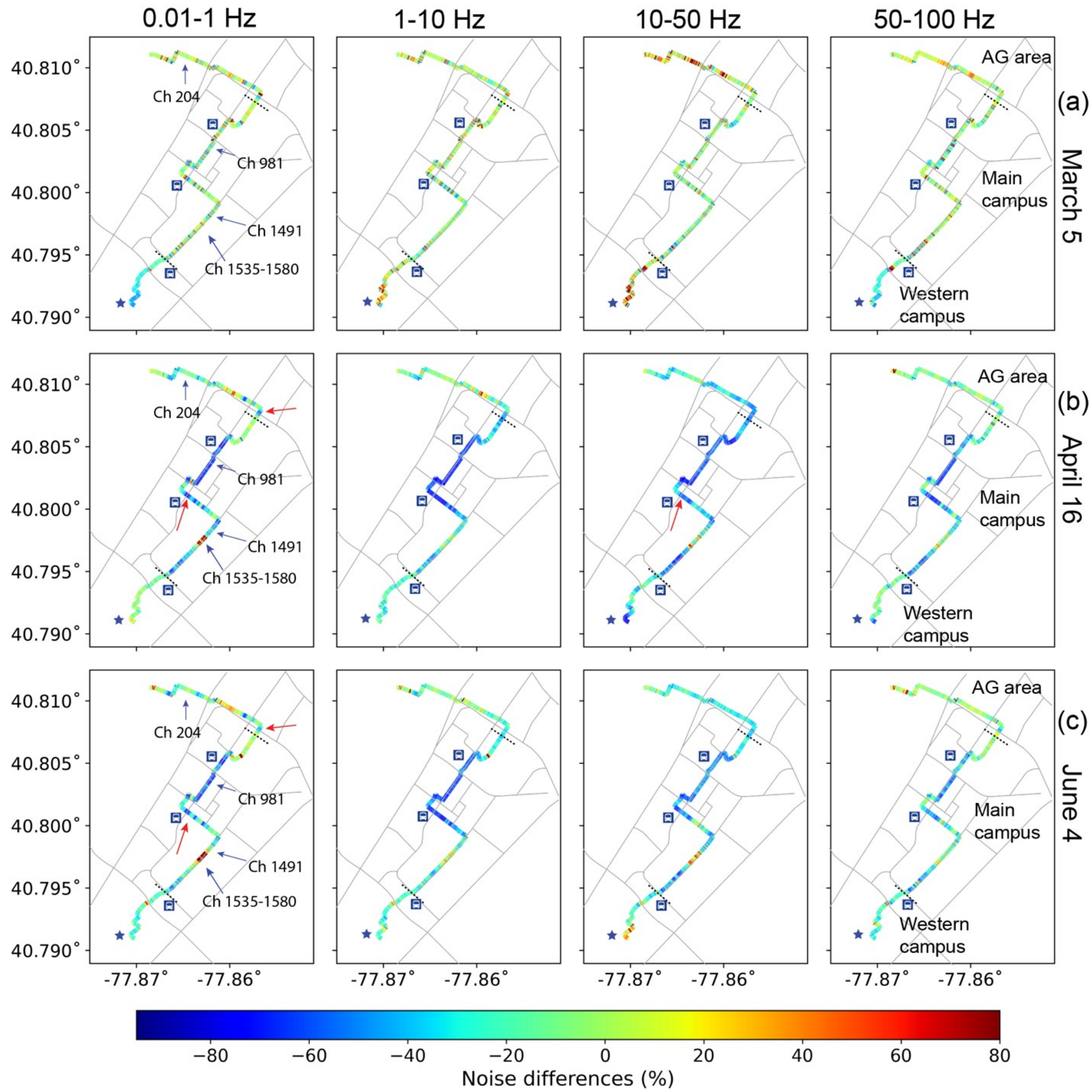

Figure 2. Time-lapse noise variations across the DAS array. The time-lapse noise difference is calculated on a given day relative to baseline: March 5 before the pandemic in the regular school semester (a), April 16 during stay-at-home order (b) and June 4 during Phase Green (c). Bus stops and the construction site are shown on the map. Red arrows indicate the noise reduction at intersections.

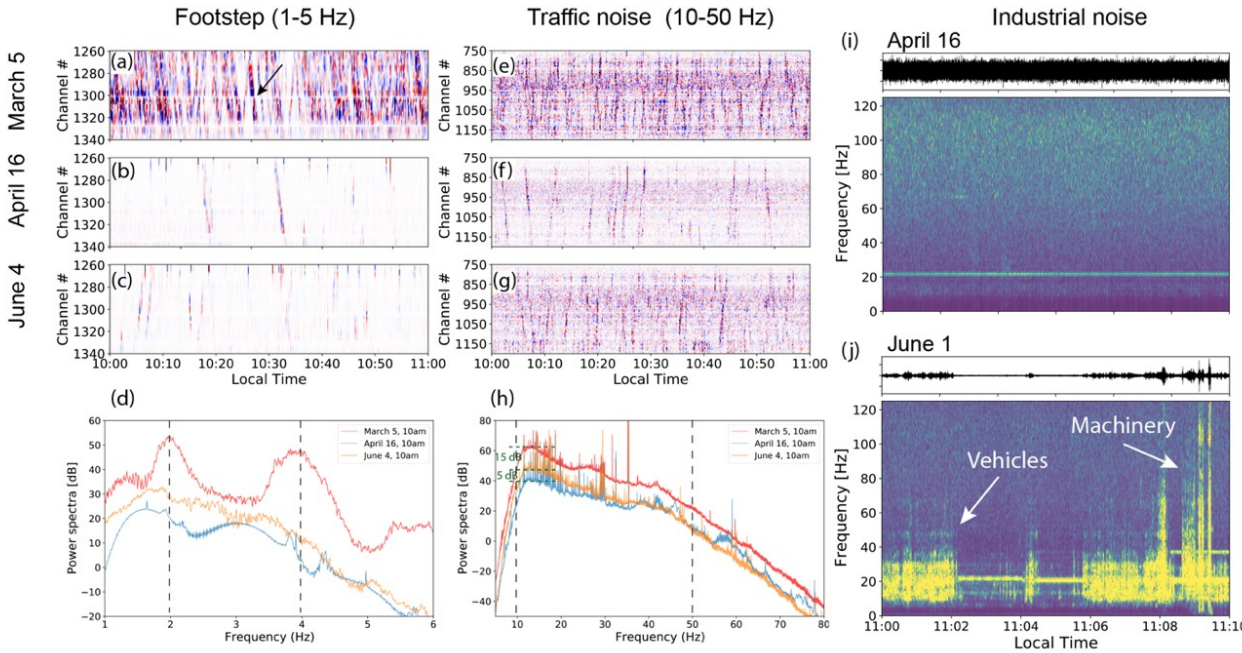

Figure 3. DAS recordings of footsteps on March 5, April 16, and June 4 (a-c) and traffic noise (e-g). Corresponding power spectra (d and h) from the seismograms above (a-c and e-g) were averaged over each subarray. Comparisons of construction-related seismic noise in the stay-at-home order (April 16, 2020) and in Phase Green (June 1, 2020). We selected DAS recordings at Ch 2100 next to the construction site (its location is indicated in Figure 1a). Raw DAS data and their time-frequency spectra maps on (i) April 16, 2020 and (j) June 1, 2020. The 20-Hz signal might be caused by the nearby air conditioner.

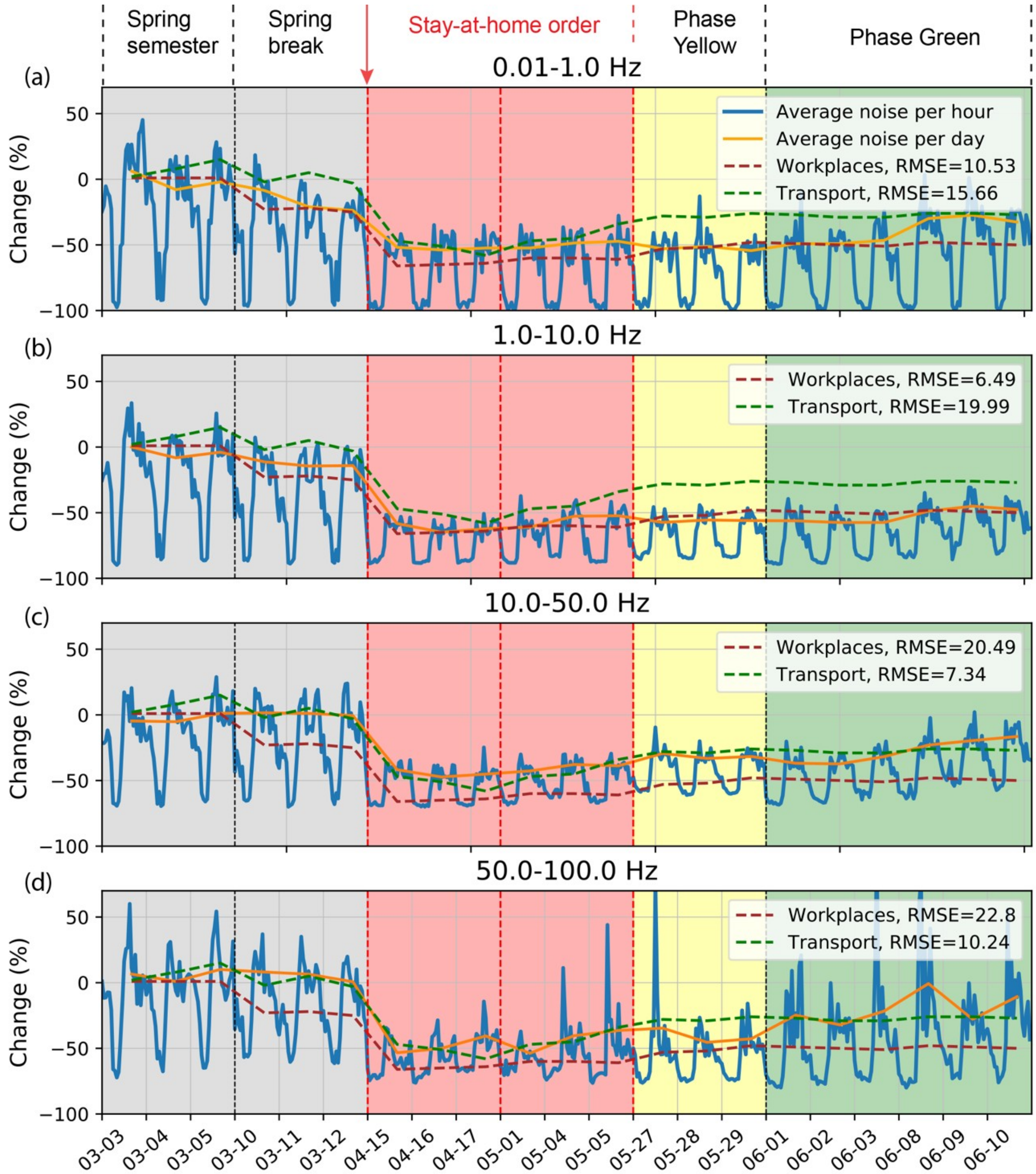

Figure 4. Noise change at Ch 981 in the frequency range of (a) 0.01-1 Hz, (b) 1-10 Hz, (c) 10-50 Hz and (d) 50-100 Hz. The daily average noise change (orange) and the mobility data from Google (dashed line) are plotted.

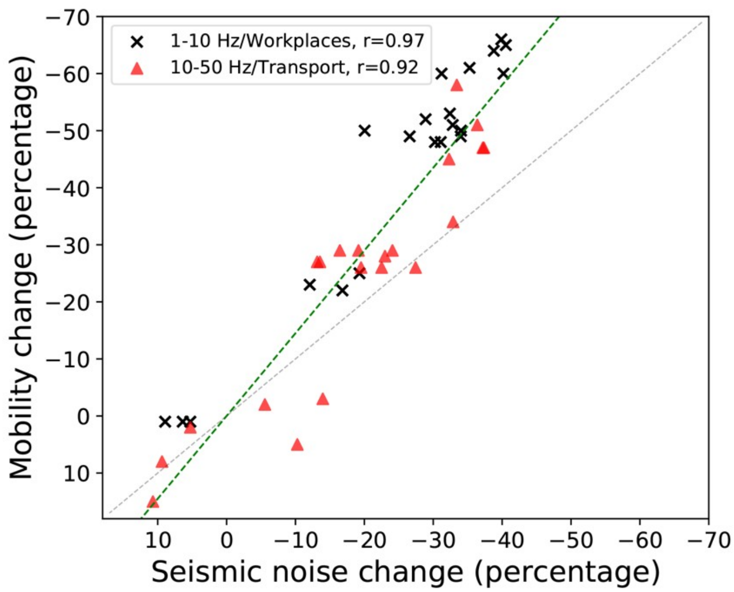

Figure 5. Plot of average time-lapse changes in seismic noise (1-10 Hz and 10-50 Hz) from all channels against with Google mobility data from workplaces and transport, respectively. Each data point represents the averaged changes on a single day (the same days in Figure 1b and 4). The green dashed line indicates the linear correlation between mobility change and seismic noise change with a ratio of 1.49. The diagonal gray line indicates a ratio of 1.