Seismic Noise Recorded by Telecommunication Fiber Optics Reveals the Impact of COVID-19 Measures on Human Activity

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Abstract

Quantifying the response of human activity to different COVID-19 measures may serve as a potential way to evaluate the effectiveness of the measures and optimize them. Recent studies reported that seismic noise reduction caused by limited human activity due to the COVID-19 lockdown had been observed with seismometers. However, it is difficult for the current seismic infrastructure in urban cities to characterize spatiotemporal seismic noise during the post-COVID-19 lockdown, because of their 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, Pennsylvania. We first show a spatiotemporal seismic noise reduction (up to 90%) corresponding to reduced human activity in different city blocks during the stay-at-home period. We also show partial noise recovery corresponding to increased road traffic and industrial machinery in phase yellow and phase green of the lockdown. Nonrecovery seismic noise in the 0.01–10 Hz band suggests the low level of pedestrian movement during phase yellow and phase green. According to a linear correlation between Google 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 activity in different blocks.

Introduction

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

Seismologically, human activity generates vibration noise with frequencies 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 multiple cities (Lecocq et al., 2020; Poli et al., 2020; Xiao et al., 2020; Yabe et al., 2020). These studies used sparsely distributed seismic stations in the cities to analyze the reduction of seismic noise attributed to the initial phase of lockdown. Surprisingly, the recorded seismic data did...
not show distinguishable difference when the level of human activity changed at certain times: (1) during early isolation before official restrictions were placed and (2) after the relaxation of restrictions (Dias et al., 2020; Pulli and Kafka, 2020).

One possible reason is that sparsely located seismic stations within the city’s large perimeter have difficulty picking up high-frequency anthropogenic noise from afar due to attenuation effects. During the COVID-19 pandemic, various sectors of the city might respond to the restrictions differently. This highly spatially varying characteristic of anthropogenic noise motivates the demand for dense seismic arrays in urban areas to provide high-resolution maps of noise variation.

Distributed acoustic sensing (DAS), a new technology converting optic fibers to dense seismic sensor arrays, could provide high-fidelity seismic strain or strain rate measurements at meter-scale spacing (Lindsey et al., 2017; Ajofranklin et al., 2019; Zhan, 2019; 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 an entire parade (motorcycles, floats, and bands), individual vehicles, footsteps, and music songs, highlighting the sensitivity of DAS-equipped fibers in the cities (e.g., Wang et al., 2020; Zhu et al., 2021).

Lindsey et al. (2020) used DAS with telecommunication fiber to detect a seismic noise reduction due to a decrease in vehicles immediately following the lockdown order in California between 1 March and 1 May 2020, and found a correlation between the urban noise level from DAS measurements and mobile phone locations.

In this article, we aim at investigating whether seismic noise recorded by DAS with unlit fiber-optic cables (dark fiber) is able to reflect the response of human activity to three levels of restrictions in Pennsylvania (lockdown, phase yellow, and phase green) between 1 March and 10 June 2020 (Detailed description of three levels of restrictions are in Text S1, available in the supplemental material to this article). To distinguish between different human activities (i.e., pedestrian movements, vehicle traffic, and construction activities) responding to the restrictions, we investigate spatiotemporal seismic noise variation in the frequency band of 0.01–100 Hz.

The DAS Array

The continuous data we use were collected by the FORESEE (Fiber-Optics For Environment Sensing) array in State College, Pennsylvania, of 4.2 km underground telecommunication fiber-optic cable deployed 1 m beneath the Pennsylvania State University campus (Fig. 1). The DAS array had a total of 2137 channels with a 10 m gauge length and 2 m channel...
spatial. The continuous strain rate measurements were sampled at 500 Hz. More details about the experiment can be found in Zhu et al. (2021). 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 16 March–15 April and 6–26 May. We analyze seismic noise variation of 21 weekdays at seven distinct time periods (three days for each group) from 3 March to 10 June 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 located at Penn State University offers opportunities to explore the social response, at the city block scale, to Pennsylvania's progressive lockdown measures that rely on voluntary community action. Penn State University was closed after spring break on 18 March 2020, and all the residents were required to stay at home, except for essential movements according to the statewide stay-at-home order from 1 April 2020. The social activity started to recover after the state official relaxation (designated phase yellow and phase green) on 27 May 2020.

Spatial Distribution of Noise Variation during COVID-19

We first present the meter-scale spatial variation of seismic noise (root mean square [RMS] strain rate, calculation details in Text S2) across the 5 km DAS array (Fig. 1). Spatially, before lockdown, seismic noise is strongest on the main campus, intermediate in the western campus, and weakest in the agricultural area (AG area). The average RMS strain rates in these three areas are 524, 403, and 205 $\text{nm/s}$, respectively. A significant drop of seismic RMS noise is observed after the implementation of the stay-at-home measure (average RMS strain rate are down to 333, 301, and 151 $\text{nm/s}$, respectively). After phase yellow, seismic noise recovers somewhat but stays at a relatively low level (average RMS strain rate in each section: 394, 322, and 168 $\text{nm/s}$).

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

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

The largest noise variation is detected on the main campus (Fig. 2b). The peak noise reduction appears in all frequency bands on 16 April, under the stay-at-home order. The largest reduction in the main campus reaches up to 90% in the 1–10 Hz frequency band. With the gradual relaxation of the COVID-19 measures, the noise level on the main campus increases but remains relatively low (about 60% in the 1–10 Hz band). Exceptions can be found around channels 1535–1580, in which the noise level is higher during the stay-at-home order, possibly because cars were allowed to enter this previously pedestrian-only area and generated stronger noise.

Both AG 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 the 10–50 Hz band, 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 and phase green) of construction-related activities.

We also find that channels around the intersections could detect large noise variation in the frequency band below 50 Hz, whereas 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).

Temporal Variation of Three Noise Sources Associated with Human Activity

Predominant anthropogenic noise sources vary in different city sectors. Our 4.2 km long dense DAS array covers workplaces (channels 1240–1440), main roads (channels 850–1110), a residential area (channels 690–830), and a less-populated area (channels 110–300) (Figs. 1b and 2). Characterizing seismic noise from specific sources can help us understand local social response to city lockdown measures. Hence, we choose specific subarrays to investigate temporal noise changes in different frequency bands due to specific human activity—walking, driving, and construction activity, by comparing seismic noise variations at three levels of COVID-19 restrictions.

To analyze the impact of the lockdown measures on footsteps, we select 1 hr data (local time 10–11 a.m.) from a
Figure 2. Time-lapse noise variations across the DAS array. The time-lapse noise difference is calculated on a given day relative to baseline: (a) 5 March before the pandemic in the regular school semester, (b) 16 April during stay-at-home order, and (c) 4 June during phase green. Bus stops (bus sign) and the construction site (blue star) are shown on the map. Red arrows indicate the noise reduction at intersections. Black-dashed lines represent the defined boundary of three sections.
subarray beneath a pedestrian-only path on the main campus on three weekdays (5 March, 16 April, and 4 June; Fig. 3). As expected, walking footstep signals show up as linear moveout events in data gathers (the black arrow in Fig. 3a) with a slow moveout (1–2 m/s). On 5 March, during the regular semester, the DAS array picked up many walking events (Fig. 3a). Contrarily, on 16 April, after the stay-at-home order was issued, only a few signals are detected at this pedestrian path (Fig. 3b). During phase green (4 June), the footstep signals barely recover despite the easing of some restriction measures. This nonrecovery is confirmed by the average spectrum plot in Figure 3d, showing the absence of peaks at 2 and 4 Hz in both 16 April and 4 June curves, which are considered as the footstep signals (Zhao et al., 2021; Zhu et al., 2021).

We next analyze traffic noise recordings (Fig. 3e–h) from a subarray beneath Curtin Road—the main road on campus. There is a significant decrease in the number of passing vehicles, when comparing data between 5 March and 16 April. This is due to the shutdown of the university, preventing people from traveling to campus. The bus service was also reduced. On 4 June, 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 (Fig. 3h): a significant drop about 20 dB of the power spectra between 10 and 50 Hz, then an increase by 5 dB. We interpreted 10–50 Hz as the frequency band of passing vehicles.

In addition, we identify higher-frequency noise associated with construction activity. On the western campus, a new parking garage and utility upgrades near the fibers were planned to be constructed from 17 December 2019 to 20 April 2021. Because of the suspension of the industrial activity during the stay-at-home measures, the data on 15 April show no detected events (Fig. 3i). After industrial activity restarted on 7 May (phase yellow), we observe strong industrial noise on 1 June in Figure 3j. The noise in the frequency band of 10–30 Hz could be identified as noise from construction vehicles. Impulses in a wide frequency band (10–100 Hz) between 11:09 and 11:10 a.m. were from machinery, which produced short bursts of vibrations.
Temporal Noise Variation during COVID-19

Here, we show the total temporal noise variations from 3 March to 10 June 2020. Figure 4 shows the time-lapse noise changes recorded by channel 981 located beneath Curtin Road on the main campus (channel 204 in Fig. S1 and channel 1491 in Fig. S2). As a comparison, seismic noise changes are plotted against the Google mobility data from workplaces and transport across the county (details in Text S3; Google, 2020). Although detailed mobility data near the fiber are unavailable, we conduct a general validation.

First, we can see that noise slightly decreased (up to 10%) during the spring break, compared to the regular spring semester in the low-frequency band (0.01–10 Hz). This decrease is attributed to minimal school activities during spring break (i.e., many students left school, and there were fewer school activities). In the 10–50 Hz band, the noise changes in both channel 981 (Fig. 4) and channel 1491 (Fig. S2c) remain flat before the stay-at-home order, whereas the change in channel 204 (Fig. S1) decreases. During spring break, the quiet roads (channel 204) are more likely to have reduced vehicle traffic, whereas the main road on campus (channels 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 only decreases at channel 1491 (Fig. S2d), which is likely caused by stopping machinery noise (from a construction site near channel 1491).

After the university closure on 18 March, daily average noise levels decrease distinctly (up to 60%) and fall to the lowest level in the whole period of the stay-at-home phase (Fig. 2 and Figs. S1 and S2). Moreover, this ubiquitous noise reduction in all frequency bands (0.01–100 Hz) reflects the quieter period and the significant reduction of noise sources due to the stay-at-home order. We infer that very limited human activity took place at the campus.

After phase yellow on 27 May, the low-frequency noise level (0.01–10 Hz) remains 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 high-frequency noise level (10–100 Hz) gradually increases, which is consistent with the mobility data (transport), suggesting the recovery of road traffic and industrial activity (e.g., shopping and construction business). After phase green, the noise in all frequency bands gradually increases by a few percentage points (1–10 Hz) to 20% (0.01–1 Hz).

We calculate the root mean square error (RMSE) between Google mobility data from two categories and noise changes in four frequency bands discussed previously (Fig. 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, and 50–100 Hz as school activities mixed with bedrock loading of vehicles (Lindsey et al., 2020); school activities; traffic; and traffic mixed with industrial activities, respectively.

Comparison to Mobility Data

To generalize the relationship between seismic noise and mobility data, we calculate an average seismic noise change for a single day by first averaging 24 hr noise changes for each channel and then averaging them across channels. Figure 5a shows a crossplot between the noise data from channels 600–1400 on main campus and the aggregated Google mobility data. The noise reduction in the frequency band of 1–10 Hz is compared with the workplace mobility data, whereas the 10–50 Hz noise-level reduction is compared with the transport mobility data. The changes of seismic noise level are almost identical to the mobility changes as \( M_{TL} = 1.14N_{TL} \), in which \( M_{TL} \) is time-lapse mobility change and \( N_{TL} \) is time-lapse noise change.

Figure 5b shows a crossplot between the noise data from channels in the less-populated areas (channels 1–600 and 1400–2137) and aggregated Google mobility data. It is clear that the seismic noise reduction is somehow smaller than the reduction in the aggregated mobility data, especially in the frequency band of 1–10 Hz. We speculate that seismic noise reduction may be underestimated in these quiet areas.

Because outside of the main campus (channels 1–600 and 1400–2137), irregular noise sources (e.g., heavy vehicles) that contaminate seismic noise recordings with anomalous peaks (see Figs. S1 and S2) are common. As a result, the average noise reduction is counteracted by the strong noise peaks. On the other hand, our results provide the evidence that seismic noises sources from the main campus tend to be less irregular (Figs. 4 and 5), similar to the mobility data, and can serve to assess the dynamic behavior of human activity.

Discussion and Conclusions

Although a general noise reduction was discovered in many cities by previous studies (Dias et al., 2020; Lecocq et al., 2020; Poli et al., 2020; Xiao 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 a seismic noise reduction in broad frequency bands (0.01–100 Hz) caused by decreased human activity
Figure 4. Noise change at channel 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. RMSE, root mean square error.
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), whereas the noise in 1–10 Hz shows no recovery until the late phase green. We interpret that after the relaxation of restrictions, residents voluntarily followed the stay-at-home guidelines (i.e., less pedestrian movement), whereas road traffic and industrial activity 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. The sensitivity of the DAS array indicates the possibility of using seismic noise variation from telecom DAS at the city block scale to evaluate local response to social restrictions.

Second, seismic noise in the low-frequency band (0.01–1 Hz, in which anthropogenic noise is weaker) is also impacted, which was not reported in previous studies using seismic networks (Lecocq et al., 2020; Poli et al., 2020; Xiao 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, California, during the COVID-19 pandemic. This reduction is likely to be the geodetic response of the roadbed to decreased vehicle loading (Jousset et al., 2018; Lindsey et al., 2020), providing an additional constraint to quantify the number of passing vehicles using dense seismic noise data. We note that long-period signals below 1 Hz could also come from far-field anthropogenic noises as well as loading from pedestrians, which are similar to geodetic signals from vehicles but much weaker and negligible.

Third, spatial variation of human activity in the meter scale is hard to obtain from sparse seismic stations due to incomplete data acquisition. In contrast, DAS could provide a high spatial resolution map of seismic noise variation, which can distinguish different human activity variation patterns between urban and suburban areas. Noise changes caused by particular human activities on different streets within each area can be further identified through the analysis of different frequency bands. For instance, the significant noise reduction on the main campus, almost 90% in the frequency band of 1–50 Hz, is attributed to few local concentrated human activities (including footsteps and road traffic) due to the required stay-at-home order. 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 activity (Fig. 3).

Finally, we find a linear correlation between mobility change and seismic noise change on the main campus. We argue that DAS seismic noise data provide high spatial resolution of the human activity compared to mobility data. Meanwhile, DAS data contain nonpersonalized information and enable urban monitoring use patterns, which protect 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 anonymously 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 state-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 distributed acoustic sensing (DAS) data used in this study are collected by the Penn State Fiber Optic forR Environmental SEnsEing (FORESEE) array of underground telecommunication fiber-optic cables. Calculated seismic noise level and raw DAS data used for plotting figures in this article are available for download at DOI: 10.5281/zenodo.4072484. The mobility data are released by Google at https://www.google.com/covid19/mobility/ (last accessed September 2020). We used ArcGIS Pro to make Figure 1a. The supplemental material for this article includes: (1) a timeline of COVID-19 in our study area, (2) methods about the calculation of the root mean square (RMS) noise changes, (3) a description of mobility data we used, and (4) two figures of temporal noise-level changes at channels 204 and 1491.

Declaration of Competing Interests
The authors declare no competing interests.

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