Supporting Information for 'Nonlinear earthquake response of marine sediments with distributed acoustic sensing'

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Text S1.

To validate the dv/v measurements obtained from the DAS cable, we also analyze the earthquake ground motions recorded by the SOB3 station. We first downloaded the data (100 Hz sampling rate) recorded by the horizontal accelerometer sensor in the axis of the cable from 159 earthquakes, which occurred within the two week time period of the DAS experiment. We are able to add 56 events to the 103 earthquakes analyzed in the main manuscript as the signal-to-noise ratio (SNR) of the accelerometer data is higher than that of the DAS data. Moreover, the largest ground motions are recorded during the M_V 5.6 (M_w 5.4) earthquake, which occurred close to the DAS cable, but is not usable in our study as the DAS data clipped (see Text and Figure S3). The SOB3 accelerometion data are processed similarly to the DAS data and we show the dv/v results for the 159 events in Figure S1a. We compute a metric as the peak ground velocity (PGV) of the bandpass filtered data divided by an estimate of V_{S30} (300 m/s) to obtain results with the unit of strain that are comparable to the results from the DAS data. We observe that the largest dv/v drops occur at frequencies of 14–20 Hz at strain values slightly above 10^{-9}, which is similar to the DAS data.

To confirm that the reliability of the analysis performed with relatively weak ground motions, we also investigate the response of the sediments to 138 earthquakes that generated stronger ground motions at the SOB3 station. The 138 earthquakes are M_w 5+ events and occurred within 300 km from the cable between 2015 and May 2021. The results are shown in Figure S1b and confirm the dv/v measurements obtained for the 159 earthquakes of the two-week time period of the DAS experiment. We observe strong dv/v drops at most frequencies above 5 Hz during the strongest ground motions and different non-linearity thresholds based on the frequency band of the ACFs.

Text S2.

The azimuthal and gauge length effects described in the main manuscript are likely to be weak for the DAS data offshore the Sanriku Coast. Shinohara, Yamada, Akuhara, Mochizuki, and Sakai (2022) converted strain data of a magnitude 3.0 earthquake recorded at channel 10265 to acceleration data and compared the resulting waveforms to the acceleration waveform recorded by the SOB3 station. They found a high similarity between the OBS and converted DAS waveforms for this event, which confirms the fidelity of the wavefield recorded by DAS.

To further confirm this, we convert the strain data of the 103 earthquakes of our dataset to acceleration by considering a constant apparent phase velocity of 2800 m/s. We then select the peak ground acceleration of the converted DAS and OBS data and display them as a function of the azimuth angle between each earthquake epicenter and the OBS station in Figure S2. First, we observe similar PGAs between the two datasets, which confirms that the reliability of the DAS data. Secondly, the azimuthal variations are also very similar, which indicates that gauge length and seismic wave azimuth angles do not impact our results. Finally, some of the differences between the two datasets are likely to be caused by the constant apparent velocity used to convert strain data to velocity. Nevertheless, this first order correction allows us to validate our approach.

Text S3.

The November 29, 2019 M_w 5.4 earthquake, which occurred in the vicinity of the cable (Figure S3a), generated the strongest ground motions during the two-week experiment. The raw DAS data are recorded as 2-byte integers. Therefore, the amplitude of the raw data varies between -32768 to 32767, which corresponds to $-\pi$ and π of phase. To retrieve strain data, the cumulative sum of the raw data needs to be computed before scaling the amplitude with a constant (Equation 1 in Shinohara et al., 2022). Unfortunately, the amplitude of the raw DAS data clipped during this event (Figure S3b), which makes impossible the conversion to strain data for this earthquake. The clipping of the data only occurs during the strongest part of the ground motion.

References

Shinohara, M., Yamada, T., Akuhara, T., Mochizuki, K., & Sakai, S. (2022). Performance of seismic observation by distributed acoustic sensing technology using a seafloor cable off sanriku, japan. *Front. Mar. Sci.*. doi: https://doi.org/10.3389/fmars.2022.844506

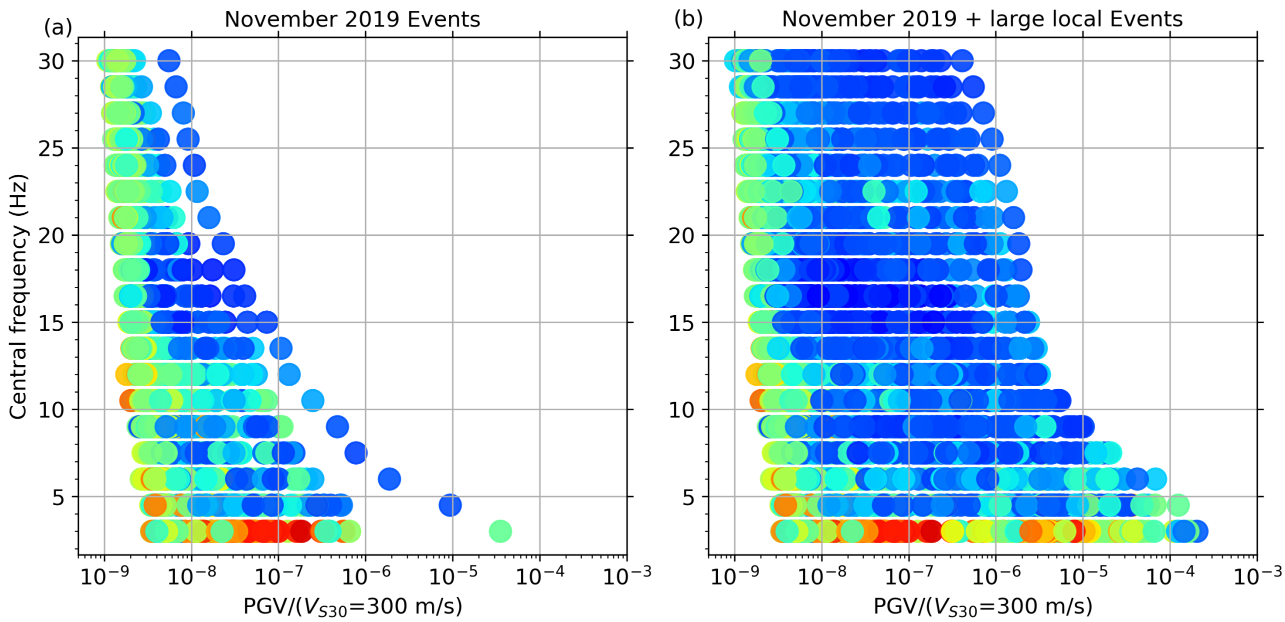

Figure S1. (a) dv/v measurements computed at the SOB3 station for 159 earthquakes which occurred during the two-week experiment. The x-axis has the unit of strain as the Peak Ground Velocity (PGV) is divided by an estimate of V_{S30} of 300 m/s. (b) dv/v measurements computed for the 159 earthquakes from November 2019 and 155 M_w 5+ events, which occurred within 300 km from the cable between January 2014 and May 2021.

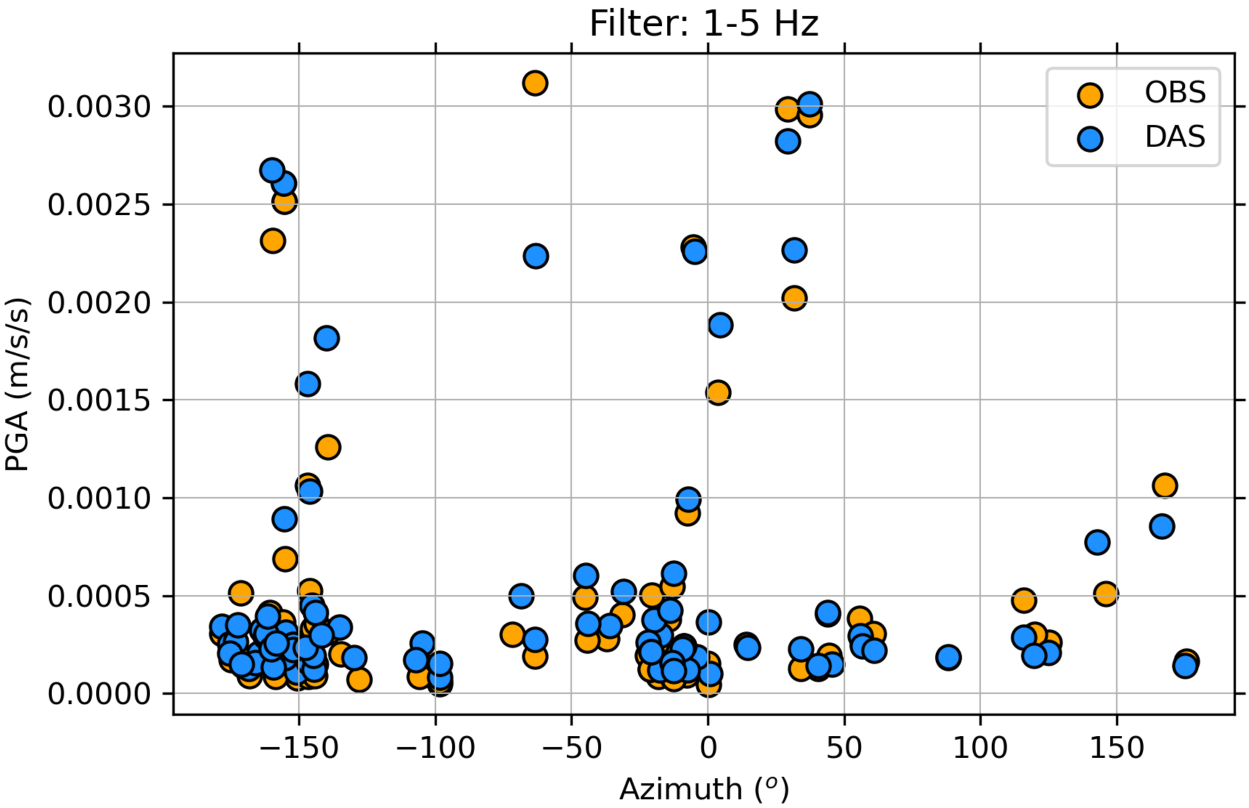

Figure S2. Peak Ground Acceleration (PGA) from the 103 earthquakes recorded at the (orange) SOB3 station and at the (blue) DAS channel 10265 after conversion to acceleration as a function of the azimuth from the epicenter. The PGAs are obtained after filtering the waveforms between 1 and 5 Hz. Zero azimuth is north.

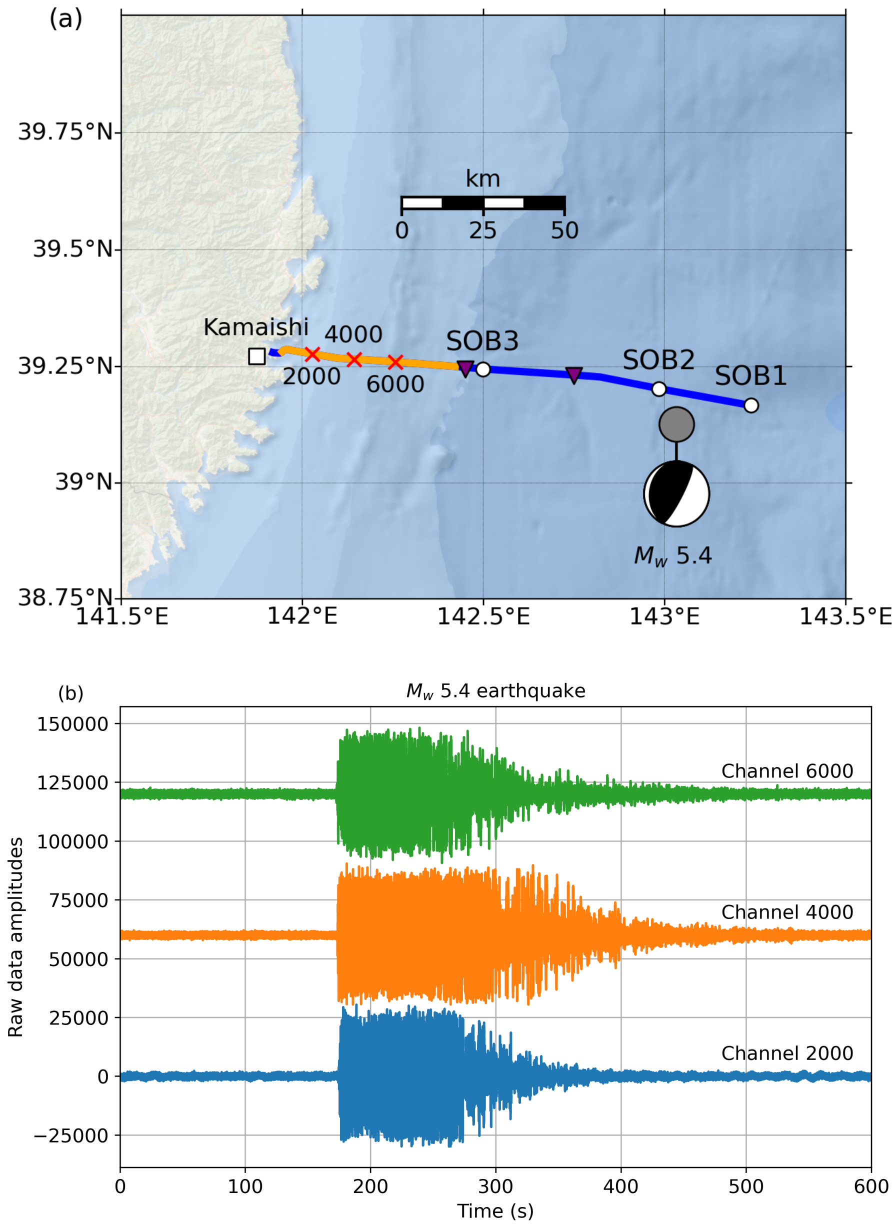

Figure S3. (b) Bathymetric map near the seafloor cable observation system. The orange line denotes the buried section of the cable used in this study, and the locations of channels 2000, 4000, and 6000 are highlighted by red crosses. The white circles and orange inverted triangles show the positions of the accelerometers and tsunami-meters, respectively. The location of the M_w 5.4 event together with its focal mechanism is also shown. (b) Raw DAS data of the M_w 5.4 event recorded at channels 2000, 4000, and 6000.