Detailed S-Wave Velocity Structure of Sediment and Crust off Sanriku, Japan by a New Analysis Method for Distributed Acoustic Sensing Data Using a Seafloor Cable with Seismic Interferometry

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**Detailed S-wave velocity structure of sediment and crust off Sanriku,
Japan by a new analysis method for distributed acoustic sensing data
using a seafloor cable with seismic interferometry**

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20

21 **Abstract**

22 S-wave velocity (V_s) structures of sediments and the uppermost crust in the landward
23 slope of a subduction zone are essential for elucidating the dynamics of the overriding
24 plate. Although distributed acoustic sensing (DAS) measurements have improved the
25 horizontal resolution of V_s structure in marine areas, the estimation has been limited in
26 the upper sedimental layer. This study imaged the structure from shallow to deep
27 sediments at a depth up to 7 km and the uppermost crust off Sanriku, Japan, with high
28 lateral resolution of 2.5km, by applying seismic interferometry to DAS data of 13 hours.
29 We grouped the DAS data into 10-km-long subarrays with 75% overlaps. We first applied
30 a frequency-wavenumber filter to the DAS data to remove DAS instrumental noise and
31 to effectively extract surface waves from short-time records. We then applied the seismic
32 interferometry method and estimated phase velocities at each subarray. The estimated
33 phase velocities of the fundamental- and first higher-mode Rayleigh waves were then
34 used to determine one-dimensional V_s structures for each subarray. The resultant 2-D V_s
35 structure was interpreted as representing sediments and crust. The upper sediment layer
36 became thick seaward, and a discontinuity between sediment and crust layers at depths

of 3–7 km showed strong lateral heterogeneities. By combining the result with the P-wave velocity (V_p) structure along the nearest survey line, we could estimate the V_p/V_s value to be 2.28–4.0 in the lowest sedimental layers. Our developed analysis method applying seismic interferometry to marine DAS data can broaden the horizons for estimating heterogeneous V_s and V_p/V_s structures of sediment layers and the upper crusts in subduction zones. These results show that the application of both frequency-wavenumber filtering and seismic interferometry to marine DAS data can be a new tool for estimating the heterogeneous V_s and V_p/V_s structure of sediment layers and the upper crust in subduction zones.

Keywords

S-wave velocity structure, Sediment and upper crust, Distributed acoustic sensing, Seismic interferometry, seafloor cable, Frequency wavenumber filter

Main Text

1 Introduction

Accurate S-wave velocity structures (V_s) of sediments and the uppermost crust in the

landward slope of a subduction zone are indispensable information for elucidating the dynamics of the overriding plate. V_s structures in a shallow region enhance the accuracy of a wide range of studies, such as hypocenter determination and consideration of rock properties. Since P-wave velocity structures (V_p) can be generally of high resolution, reliable estimation of S-wave velocities should contribute to an accurate ratio of P- and S-wave velocities (V_p/V_s), which is useful information for the estimation of rock properties (Ayres and Theilen 1999).

In the subduction zone of the Japan trench, spatially high-resolution V_p structures of sediment and upper crust were obtained in space by the recent development of detailed seismic surveys (Miura et al. 2003; Takahashi et al. 2004). However, the estimation of V_s structures has been limited. Seismic surveys in the Japan trench could estimate V_s structures based on clear recordings of P to S conversion waves (Fujie et al. 2018).

Although both seismic interferometry and receiver function methods are useful for estimating V_s with ocean bottom seismometers (OBSs) records (Akuhara et al. 2020; Yamaya et al. 2021; Yao et al. 2011), it has been difficult to obtain a high-resolution spatial V_s model because the spatial density of observation stations in marine areas does

69 not meet this quality.

70 In recent years, distributed acoustic sensing (DAS) measurements have been applied to
71 seismic observations (e.g., Zhan 2020). DAS measurements enable us to measure strain
72 velocities with spatially very high resolution over a long distance. The DAS
73 measurement is performed on both the land and seafloor. For example, Dou et al. (2017)
74 estimated shallow shear wave velocity structures by applying the ambient noise method
75 to DAS records on land. In a marine area, Spica et al. (2020) estimated the V_s structure
76 of shallow sediments (down to 3 km) by applying the frequency–wavenumber (FK)
77 analysis to the seafloor DAS measurement obtained off the Sanriku coast of Japan.
78 However, their estimation of V_s structures was limited to a shallow portion of
79 sediments. It is necessary to obtain the V_s structure of all sediment and the upper crust
80 for the research of V_p/V_s ratios. The phase velocity of overtone or long period Rayleigh
81 waves is useful for estimating a deep part of the sediment and crust, since the phase
82 velocities of these waves are sensitive for V_s in the deep part.

83 This study applied a seismic interferometry method to seafloor DAS records to extract
84 overtone or long-period (> 5 sec) Rayleigh waves. We also propose a practical method

for extracting surface waves in a low-frequency range from short-time records with FK filtering. We then estimated the phase velocities from the extracted Rayleigh waves. Finally, we obtained a 2-D V_s structure model of sediment layers and the upper crust off the Sanriku coast of northeast Japan.

2 Data and Methods

2.1 Data

In 1996, the Earthquake Research Institute of the University of Tokyo installed a seafloor seismic tsunami observation system using an optical fiber cable at Sanriku offshore (Figure 1). As the system contains six dark fibers, DAS measurement has been conducted using a DAS interrogator unit of AP sensing (Cedilnik et al. 2019) since 14 February 2019. The data were recorded at a sampling frequency of 500 Hz, and the duration of the observations in this study was selected to be about 13 hours. The sensing range, spatial resolution, and gauge length were 100 km, 5.1 m, and 40.79 m, respectively. Shinohara et al. (2019) and Spica et al. (2020) described the cable setup and measurement quality of this DAS system.

2.2 Calculate CCFs with an FK filter

101 Before calculating and stacking cross-correlation functions (CCFs) of DAS background
102 noise records, we divided the whole dataset of the DAS array into subarray ones (Figure
103 1). We decimated the original records by first reducing the sampling frequency from
104 500 Hz to 2 Hz; 10 adjacent data were then stacked to enhance signal-to-noise ratios
105 (SNRs) after filtering the anti-spatial aliasing. As a result, the spatial interval of the data
106 became 51 m.

107 To compute CCFs, we first divided continuous records into 10-minute time window
108 segments. We allowed for a 50% overlap of each segment to improve its SNR. We
109 computed the weighted average of the cross spectra between two channels, following
110 Takagi et al. (2021) and Takeo et al. (2013, 2014). This processing was conducted in the
111 frequency domain. To avoid any earthquake signals, we calculated the mean power
112 between 0.025 and 0.2 Hz in the frequency domain for each time window, and any
113 datasets whose amplitude exceeded 10 times the amplitude for the previous time
114 window were discarded. Takeo et al. (2013) provided more detailed explanations for the
115 calculation of CCFs.

116 In general, DAS instrumental noise has a coherent phase at the same time for all stations

(Tribaldos and Franklin 2021). These noises particularly affect seismic interferometry studies. In this study, we applied an FK filter to DAS data to remove this zero-lag noise and enhance the SNR before calculating and stacking the CCFs. Given that the high spatial density of DAS data enables us to apply spatial Fourier transformation, we conducted a 2-D Fourier transformation in the FK domain. The zero-lag noise, which has an infinity phase velocity, is mapped to the zero wavenumber in the FK domain. We designed an FK filter $w(f, k)$ as:

$$w(f, k) = g(f, k, c_{\min}) * (1 - s(f, k, c_{\max})), \quad (1)$$

where $g(f, k, c_{\min})$ is a 10 % Tukey window to eliminate signals slower than the cut-off minimum phase velocity $c_{\min}$. $g(f, k, c_{\min})$ is defined as:

$$g(k, f, c_{\min}) = \begin{cases} 1, & \text{for } -0.4k_{\max} < k < 0.4k_{\max} \\ 0, & \text{for } k < -0.5k_{\max} \text{ or } k > 0.5k_{\max} \\ \frac{1}{2} [1 + \cos\{\pi(1 - \frac{k}{0.1k_{\max}})\}] , & \text{otherwise} \end{cases}, \quad (2)$$

132

133 where $k_{\max} = 4\pi f / c_{\min}$. Furthermore, $s(f, k, c_{\max})$ is the 8-th order Kaiser filter to
134 remove the signal faster than the maximum phase velocity $c_{\max}$, including the zero-lag
135 noise. In this study, to enhance the surface wave signals, we set $c_{\min}$ and $c_{\max}$ to be
136 0.35 km/s and 4.0 km/s, respectively.

137 **2.3 Phase velocity estimation**

138 We adopted the spatial auto-correlation (SPAC) method to estimate phase velocity (Aki
139 1957; Okada 2006; Nishida et al. 2008b) because the SPAC method represents the
140 observed cross-spectra assuming a laterally homogeneous structure and a homogenous
141 source distribution. According to Nakahara et al. (2021), the synthetic cross-spectrum
142 for radial strain records (e.g., DAS) is defined as:

143

$$144 \quad S_{ij}^{\text{syn}}(\omega, c_R, c_L) = A_R(\omega) \left[3J_0\left(\frac{\omega}{c_R} d_{ij}\right) - 4J_2\left(\frac{\omega}{c_R} d_{ij}\right) + J_4\left(\frac{\omega}{c_R} d_{ij}\right) \right] + B_L(\omega) \left[J_0\left(\frac{\omega}{c_L} d_{ij}\right) - J_4\left(\frac{\omega}{c_L} d_{ij}\right) \right], \quad (3)$$

145

146 Where ω is the angular frequency, A_R is the power spectrum for Rayleigh wave, B_L
147 is the power spectrum for Love wave, J_n is the nth-order Bessel function of the first

kind, d_{ij} is the distance between i th and j th channels, c_R is the phase velocity of the Rayleigh wave, and c_L is the phase velocity of Love wave. In Equation 3, the first and second terms represent the Rayleigh and Love waves, respectively. In general, Love waves have less energy than Rayleigh waves at a period range below 0.1 Hz (Nishida et al. 2008a). Furthermore, as mentioned by Nakahara et al. (2021), Rayleigh waves predominate in the far field. The envelope of the Rayleigh waves term decays with an order of $d^{-1/2}$, while Love-wave term decays with an order of $d^{-3/2}$ in the far field. For these reasons and given the small, estimated contribution of the Love wave terms, we therefore obtained our misfit function E as:

$$L2(\omega, c_R) = \sum_{ij} \left(\text{Re}[S_{ij}^{\text{obs}}(\omega)] - S_{ij}^{\text{syn.}}(\omega, c_R) \right)^2, \quad (4)$$

$$E(\beta_l, h_l) = \frac{1}{\omega} \int L2(\omega, c_R(\omega; \beta_l; h_l)) d\omega, \quad (5)$$

where $S_{ij}^{\text{obs}}(\omega)$ and $S_{ij}^{\text{syn.}}(\omega)$ are the observed and synthetic cross-spectra between i th and j th channels calculated from the equation 3, respectively. β_l and h_l are the Vs and thickness at the l th layer, respectively. We followed the methods by Takeo et al. (2022)

164 and Yoshizawa & Kennett. (2002) to estimate the phase velocity model. β_l and h_l are
165 assumed to be model parameters for minimizing $E(\beta_l, h_l)$ in Equation 5 by smoothing
166 the dispersion curve. To search for the sets of model parameters for minimizing the
167 value of the misfit function, we adopted the simulated annealing algorithm of Goffe et
168 al. (1994) as a global optimizer for searching for the minimum value of Equation 5. To
169 avoid numerical instability, we constrained the V_s at each layer, which was greater than
170 80% of that of the layer directly above.

171 In practice, we estimated the phase velocity and evaluated the errors in the estimated
172 phase velocity. First, we estimated the dispersion curves of phase velocity from cross-
173 spectra for all pairs of channels for each subarray. We then obtained a 1-D model with
174 six layers, where the deepest layer had infinite thickness for each subarray. We adopted
175 the scaling relationship between V_p , V_s , and density from Brocher's (2005) results.

176 Next, searching by trial and error, we divided the subarrays into two groups according
177 to the distances from the coast. The dispersion curves of the phase velocity were
178 estimated using the fundamental mode of the Rayleigh wave only for one group, which
179 has distances ranging from 35 km to 50 km from the coast. For another group with

distances ranging from 50 km to 75 km, the fundamental mode and the first higher mode of Rayleigh wave were used to obtain a dispersion curve. Synthetic phase velocities were calculated using DISPER80 (Saito 1988). Furthermore, we used the bootstrap method (Efron 1992) to estimate errors. We aggregated station pairs randomly selected from all station pairs, allowing for overlap for a bootstrap sample. Here, we calculated the standard deviation of 100 dispersion curves estimated from each of the 100 bootstrap samples. The V_s structures estimated from the data of all pairs of channels for each subarray were used as the reference model.

2.4 Inversion of the S-wave velocity structure

From the phase velocity of the Rayleigh wave estimated by seismic interferometry, a 1-D V_s isotropic model was obtained. The 1-D V_s structure was determined by minimizing the misfit function E , as defined by:

$$E = \sqrt{\frac{1}{N} \sum \left[\frac{c_{obs}(\omega) - c_{syn}(\omega; \beta_l; h_l)}{c_{err}(\omega)} \right]^2}, \quad (6)$$

196

197 where N is the number of estimated phase velocities. c_{obs} , c_{syn} and c_{err} indicate the
198 observed, synthesized, and uncertainty of the phase velocity, respectively. To obtain a
199 stable result, only a frequency band with phase velocities with an error lower than 0.1
200 km/s was used for the inversion analysis. We again set the V_s (β_l) and thickness (h_l)
201 as the model parameters to minimize Equation 6. We then used the simulated annealing
202 algorithm method to obtain the optimal model parameters. The bootstrap average
203 models estimated from the phase velocity estimation were used as the reference model.
204 To estimate errors, we used the bootstrap method once again. Here, we aggregated the
205 final dispersion curve randomly selected from the 100 dispersion curves estimated in
206 the previous section (Takeo et al. 2013).

207 **3 Results and Discussion**

208 We computed the CCFs between all possible pairs of each subarray. The CCFs clearly
209 showed a surface wave (Figure 2). The group velocities of about 0.5 km/s were much
210 slower than the surface waves in land observations in the same period range. The
211 surface wave with low velocity corresponded to a special type of Rayleigh wave or

212 Scholte wave (Hovem et al. 2012; Bagheri et al. 2015) because the Love wave had less
213 energy than the Rayleigh wave in the period range below 0.1 Hz. The CCFs with the FK
214 filter had a much higher SNR than those without the FK filter. For the estimation of
215 SNR, the method of Bensen et al. (2007) was used.

216 We selected the dispersion curve from the CFFs (Figures 3-A and 3-E). Extracting
217 Rayleigh waves by interferometry enabled us to stably estimate dispersion curves with
218 errors less than 0.1 km/s by bootstrap. Near the coast (Figure 3-A), the fundamental
219 Rayleigh wave was dominant in the frequency range between 0.20 and 0.5 Hz. By
220 contrast, in the case of an offshore subarray (Figure 3-E), both fundamental (0.5–0.1
221 Hz) and 1st higher mode (0.5–0.2 Hz) Rayleigh waves were dominant. This result
222 clearly indicates that the thickness of the low- V_s layer differs between near-coast and
223 offshore areas. We determined the V_s structure using only the phase velocities of the
224 fundamental mode of Rayleigh waves in the near-coast area at distances between 30 km
225 and 50 km. In the area where the distance was greater than 50 km from the coast, both
226 the fundamental and first higher modes of the Rayleigh waves were used for phase
227 velocity estimation.

228 We inverted the measured phase velocities into 1-D V_s structures (Figure 3) below each
229 subarray. The 1-D V_s structures (Figures 3-B and 3-F) and normalized V_s sensitivity
230 kernels (Figures 3-C, 3-G, and 3-I) of the Rayleigh waves were calculated. Errors were
231 calculated using the bootstrap method. A small error in the depth range, whose V_s
232 values were slower than 2.0 km/s were estimated. Synthetic phase velocities calculated
233 by DISPER80 using the 1-D V_s inversion results were consistent with the observations
234 (Figures 3-D and 3-H). Given that the sensitivity kernel had high sensitivity in the depth
235 range of V_s slower than 2.0 km/s, our inversion provided a V_s structure with small
236 errors at the depth range of V_s slower than 2.0 km/s. By contrast, layers of V_s greater
237 than 2.0 km/s have uncertainty. However, the V_s sharply increases to greater than 2.0
238 km/s at the boundaries, and the error range for the lowermost layer does not overlap
239 with that of the upper layers. Nevertheless, the depth of discontinuity between the
240 lowermost layer and the upper layer was estimated with high resolution.

241 Finally, a 2-D V_s structure model (Figure 4) was obtained from the 1-D V_s structures at
242 each subarray. The 2-D structure model was composed of four layers. The V_s of the first
243 and second layers at depths of 0–1 km below the sea floor were slower than 0.6 km/s

244 and approximately 0.7 km/s, respectively. The V_s of the third and fourth layers at depths
245 of 2–6 km below the sea floor were 1.75 km/s and greater than 2.0 km/s, respectively.

246 We compared our 2-D V_s structure (Figure 4) with the V_s and V_p structures obtained by
247 other studies to interpret these layers. The V_s values of the first and second layers were
248 smaller than 0.6 km/s and about 0.7 km/s, respectively, and the velocities are consistent
249 with the results of a study by Spica et al. (2020). Takahashi et al. (2004) provided the
250 V_p structure estimated by refraction surveys along a profile parallel to our DAS cable.

251 Takahashi et al.'s (2004) profile was positioned northward and had a distance of about
252 20 km from the seafloor cable. The V_p of the first and second layers were determined as
253 1.7 and 2.3 km/s, respectively, and the layers were interpreted as Neogene sediment by
254 Takahashi et al. (2004), Kodaira et al. (2017), and Spica et al. (2020). The thickness of
255 the first and second layers increased seaward in a distance range from 30 km to 55 km.

256 This increase in thickness is also consistent with the results of a study by Spica et al.
257 (2020). However, the thickness of the first and second layers showed no large variation
258 in the distance range between 55 and 80 km.

259 The third layer was thick (~1 to ~5 km) in the distance range from the coast from 30 to

260 55 km. However, the thickness of the third layer was small (~5 to ~3 km) in a distance
261 range from 55 to 65 km. At distances between 65 km and 75 km, the third layer
262 disappeared. These lateral heterogeneities of the third layer were also shown in the Vp
263 model by Takahashi et al. (2004). The discontinuity between the third and fourth layers
264 can be interpreted as the boundary between sediments and the island arc uppermost
265 crust because the depth of the interface between the third layer and the fourth layer is
266 consistent with that reported by Takahashi et al. (2004). Below the landward slope off
267 the Japan trench at Tohoku, it is known that the sediments are large lateral
268 heterogeneous layers perpendicular to the Japan trench. (Ito et al. 2004; Takahashi et al.
269 2004).

270 Although our profile and the profile of Takahashi et al. (2004) are 20 km apart, we
271 estimated the Vp/Vs ratio of the third layer. Given that Vs was 1.1–1.75 km/s from our
272 results, and Vp was estimated to be 4.0–4.4 km/s by Takahashi et al. (2004), Vp/Vs ratio
273 in the third layer would be 2.28–4.0. However, Vp/Vs ratio of the fourth layer was
274 smaller than 2.5 because Vs and Vp of the fourth layer were faster than 2.0 and 5.0 km/s,
275 respectively. Fujie et al. (2018) estimated that the Vp/Vs ratio of the oceanic crust was

276 lower than 1.9 by seismic refraction. By contrast, Kodaira et al. (1996) estimated the
277 V_p/V_s value of the upper crust to be 1.67–1.78 at the Lofoten passive continental margin
278 in northern Norway. The estimated V_p/V_s value of the third layer in our study was
279 higher than their results for oceanic igneous crusts. However, Chian and Loudon (1994)
280 showed a V_p/V_s ratio of 4.0 for the sediment layer in south-western Greenland, and
281 Kodaira et al. (1996) found the V_p/V_s value of the sediment layers to be 3.0–5.0 in
282 northern Norway. As described by Kodaira et al. (1996), unconsolidation is most
283 effective for the large V_p/V_s ratio of sediment layers. Some aftershocks of the 2011
284 Tohoku-oki earthquake occurred in the fourth layer (Figure 4), whereas there was no
285 seismicity in the upper layers. As a result, the third layer can be interpreted as a
286 sediment layer, and the interface between the third layer and the fourth layer represents
287 the upper surface of the igneous crust.

288 The estimation of V_s structures using DAS records in previous studies has been limited
289 to a shallow part of crusts. Spica et al. (2020) estimated the V_s structure to be up to 3
290 km in depth. The seismic interferometry with FK filtering to DAS data enables the
291 determination of phase velocities of surface waves whose periods are longer than those

of previous studies. Therefore, we could obtain an S-wave structure in depth up to 8 km using the DAS data with high spatial resolution. Yamaya et al. (2021) estimated a three-dimensional V_s structure using data from an OBS network with an interval distance of 6 km off Ibaraki, Japan, by a tomography method. Generally, the resolution of seismic tomography depends on the spatial density of the stations. By contrast, the spatial horizontal resolution of the 2-D V_s structure in this study is believed to be higher due to the high spatial density of the observation. V_s structures in oceanic crusts have usually been estimated by observation of P to S conversion waves during seismic surveys or seismic interferometry using spatially dense OBSs data. Our method offers a new approach to determine the V_s of shallow structures with high spatial resolution in marine areas from short-term DAS data using a seafloor cable. A shallow V_s structure in a marine area with high resolution by our method leads to a detailed distribution of V_p/V_s ratio in a shallow region, which is useful for considering tectonics and rock properties.

5 Conclusions

The information of V_s is important to understand the rock properties of the upper crust

308 and sediments on the seafloor. We applied the seismic interferometry method to DAS
309 records with a recording period of 13 hours by seafloor cable installed off Sanriku,
310 Japan. Applying the FK filter to the DAS data before calculating the CCFs effectively
311 enhances surface waves. The phase velocities of the Rayleigh waves were calculated by
312 the SPAC method. Finally, we inverted the V_s structure from the phase velocities of the
313 Rayleigh waves obtained from seismic interferometry. The V_s structures of the sediment
314 layers and the upper crust were consistent with those determined by refraction surveys.
315 The seismic interferometry method with DAS data collected through seafloor cables
316 could estimate V_s structures with high spatial resolution.
317 To explore the V_s structure of sediment layers, seismic interferometry and receiver
318 function methods have been widely conducted using OBS data. However, their spatial
319 resolution is constrained by the spatial density of the installed OBSs. By contrast, a V_s
320 structure with high spatial resolution can be estimated from short-term DAS records by
321 applying the seismic interferometry method. Our results showed a new approach to
322 estimating the heterogeneous V_s structure of sediment layers and the upper crust in
323 subduction zones.
324

325

326 **Declarations**

327 **Ethics approval and consent to participate**

328 Not applicable.

329 **Consent for publication**

330 Not applicable.

331 **List of abbreviations**

332 V_S : S-wave velocity

333 V_P : P-wave velocity

334 V_P/V_S : ratio of P- and S-wave velocities

335 DAS: distributed acoustic sensing

336 FK: frequency–wavenumber

337 CCFs : cross-correlation functions

338 SNRs : signal-to-noise ratios

339 SPAC : spatial auto-correlation

340 OBSs : ocean bottom seismometers

341

342 **Availability of data and materials**

343

344 The DAS observations were performed as part of the Earthquake and
345 Volcano Hazards Observation and Research Program (Earthquake and
346 Volcano Hazard Reduction Research) by the Ministry of Education,
347 Culture, Sports, Science and Technology of Japan. These data are
348 available from the corresponding author on request.

349

350 **Competing interests**

351 The authors acknowledge that there are no conflicts of interest recorded.

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Authors' contributions

SF played a leading role in this study, including data processing, analysis, and completion of the manuscript. MS and TY led the temporal DAS observation and interpreted the results. KN, AK, and KY contributed to develop the analysis method and interpreted the results. All authors read and approved the final manuscript.

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(Hunter 2007) and Generic Mapping Tools (Wessel et al. 2019).

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500 **Figure legends**

501 **Figure 1**

502 **Short title :** Location of the seafloor cable containing optical fibers in the off-Sanriku

503 region, Japan.

504 **Detailed legend**

505 Location of the seafloor cable containing optical fibers in the off-Sanriku region, Japan.

506 The black line indicates the seafloor cable installed by the Earthquake Research

507 Institute, the University of Tokyo. The red dots indicate the center locations of the

508 subarrays to calculate the CCFs in this study.

509

510 **Figure 2**

511 **Short title:** Calculated CCFs.

512 **Detailed legend:**

513 Calculated CCFs. Each trace was normalized by its amplitude. (A) and (B) – CCFs at a

514 distance of 39.94 km from the coast without and with an FK filter, respectively. The

515 frequency range was between 0.17 and 0.50 Hz. (C) and (D) – CCFs without and with

516 an FK filter at 59.96 km from the coast in the frequency range between 0.10 and 0.25

517 Hz. SNR indicates the signal-to-noise ratios calculated by Bensen's (2007) method. The

518 dashed lines indicate an apparent velocity of 0.5 km/s. The FK filter improves SNR

values and enables us to extract surface waves effectively.

Figure 3:

Short title: Phase velocity, V_s structures, and sensitivity kernel.

Detailed legend:

(A) and (E) – Normalize residuals and estimation phase velocity at subarrays from the coast of 32.43 and 67.68 km, respectively. The error bars represent the uncertainties estimated by the bootstrap method. The white dots and cross makers indicate errors less than and more than 0.1 km/s, respectively. We used phase velocity only with an error less than 0.1 km/s for our inversion analysis. (B) and (F) – V_s structures at subarrays from the coast of 32.43 and 67.68 km. (D) and (H) – The white dots and green lines indicate the observed and estimated phase velocities. The errors were estimated by the bootstrap method. (C) – The normalized V_s sensitivity kernel of the fundamental Rayleigh wave at 32.43 km from the coast. (G) and (I) – The normalized V_s sensitivity kernels of fundamental and first higher mode Rayleigh waves at 67.68 km from the coast.

535

536 **Figure 4:**

537 **Short title:** 2-D V_s structure estimated from phase velocity information.

538 **Detailed legend:**

539 2-D V_s structure estimated from phase velocity information. The white circles indicate

540 the aftershocks off the Pacific coast of the Tohoku Earthquake determined by pop-up

541 OBSs (Shinohara et al., 2012). The aftershocks within a box of 40 km in width on both

542 sides along the fiber cable are projected onto this profile.

543

544 **Preparing additional files**

545 Additional figures.

546

Figures

Figure 1

Short title : Location of the seafloor cable containing optical fibers in the off-Sanriku region, Japan.

Detailed legend

Location of the seafloor cable containing optical fibers in the off-Sanriku region, Japan. The black line indicates the seafloor cable installed by the Earthquake Research Institute, the University of Tokyo. The red dots indicate the center locations of the subarrays to calculate the CCFs in this study.

Figure 2

Short title: Calculated CCFs.

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Calculated CCFs. Each trace was normalized by its amplitude. (A) and (B) – CCFs at a distance of 39.94 km from the coast without and with an FK filter, respectively. The frequency range was between 0.17 and 0.50 Hz. (C) and (D) – CCFs without and with an FK filter at 59.96 km from the coast in the frequency range between 0.10 and 0.25 Hz. SNR indicates the signal-to-noise ratios calculated by Bensen's (2007) method. The dashed lines indicate an apparent velocity of 0.5 km/s. The FK filter improves SNR values and enables us to extract surface waves effectively.

Distance from the coast : 32.43 [km]

Distance from the coast : 67.48 [km]

Figure 3

Short title: Phase velocity, Vs structures, and sensitivity kernel.

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