Development of surface-wave monitoring system for leaked CO₂ using a continuous and controlled seismic source

Tatsunori Ikeda^{1*}, Takeshi Tsuji¹, Toshiki Watanabe² and Koshun Yamaoka³

1. International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, Motoooka, Nishi-ku, Fukuoka 819-0395, Japan.

2. Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan.

3. Earthquake and Volcano Research Center, Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan.

*Corresponding author. E-mail: ikeda@i2cner.kyushu-u.ac.jp

International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, Motoooka, Nishi-ku, Fukuoka 819-0395, Japan.

TEL: +81-92-802-6721

FAX: +81-92-802-6721

19 **Abstract**

20 To detect CO₂ leakage from CO₂ geological storage, we describe a seismic monitoring method using
21 a continuous and controlled seismic source system, the Accurately Controlled Routinely Operated
22 Signal System (ACROSS). The method applies surface-wave analysis to monitor the shallow
23 subsurface from the temporal-variation (time-variation) of surface-wave phase velocity. Our
24 numerical simulation study for CO₂ leakage through fault zones indicated that the spatial distribution
25 of leaked CO₂ can be estimated from small temporal-variation of local phase velocities (~1-3 %). To
26 demonstrate the method in a field case, we analyzed continuous seismic records acquired with
27 ACROSS. We clearly extracted a dispersion curve of surface waves in the frequency range excited
28 by the ACROSS (5.015–15.015 Hz). In particular, we obtained reliable estimates of phase velocities
29 in 10-15 Hz frequency range, in which the time-variation of phase velocities was better than 1 %
30 accuracy. This temporal stability was sufficient to allow us to detect changes in phase velocities
31 associated with CO₂ leakage before leaked CO₂ reached the surface.

32

33 **Keywords:** CO₂ leakage; CCS; monitoring; surface waves; ACROSS

34

35 **1. Introduction**

36 To achieve reliable operation of carbon capture and storage (CCS) projects, subsurface reservoirs
37 and injected CO₂ must be monitored during and after CO₂ injection. The distribution and migration
38 of injected CO₂ can be successfully monitored on the basis of a time-lapse (4D) seismic survey using
39 artificial sources, such as air-gun or vibroseis surveys (e.g., Chadwick et al., 2010). A major problem
40 for such time-lapse surveys is their cost, arising from the large number of surveys required to detect
41 the temporal-variation (time-variation) of seismic velocity associated with CO₂ injection. Time-lapse
42 analysis using ambient noise is an alternative approach for monitoring CCS reservoirs (e.g.,
43 Boullenger et al., 2015; Draganov et al., 2012; Gassenmeier et al., 2015; Tsuji et al., 2015). This
44 technique is attractive because of its continuity over time and cost efficiency for data acquisition.
45 However, time-lapse results are affected by the uncertainty of the ambient noise source, which is
46 difficult to resolve.

47 One promising method for obtaining continuous seismic data using a well-controlled source is the
48 Accurately Controlled Routinely Operated Signal System (ACROSS), an apparatus developed for
49 detecting time-variation in the seismic velocity of the Earth's interior (Kumazawa and Takei, 1994;
50 Yamaoka et al., 2001). ACROSS generates seismic signals with a rotating eccentric mass. Changes
51 in seismic velocity have been successfully detected with ACROSS surveys. Ikuta et al. (2002) and
52 Ikuta and Yamaoka (2004) used it to detect sudden decreases of S-wave velocity associated with the

53 2000 Western Tottori earthquake (Mw 6.6) and the 2001 Geiyo earthquake (Mw 6.4). Kasahara et al.
54 (2013) also used it to detect the delay of P-waves due to the injection of 80-t of air. More recently,
55 Maeda et al. (2015) used it to detect the energy decrease of Green's functions associated with
56 eruptive activity at Sakurajima volcano, Japan.

57 In monitoring CCS projects, it is crucial to detect CO₂ leakage from the ground or seafloor, which
58 requires a robust monitoring method for the shallow subsurface. Surface-wave analysis techniques
59 developed for characterization of near-surface S-wave velocity (e.g., Ikeda et al., 2015; Socco et al.,
60 2010; Xia et al., 2009) present good candidates for such a method. Surface-wave methods are
61 successful even in offshore environments as CO₂ storage sites (e.g., Ikeda and Tsuji, 2015).

62 This paper describes a method for detection of CO₂ leakage in CO₂ geological storage using
63 ACROSS. In our study, the shallow subsurface was monitored by applying time-lapse surface-wave
64 analysis to continuously observed seismic data. We performed a numerical simulation study of CO₂
65 leakage to investigate the sensitivity of our proposed method in detecting the spatial distribution of
66 leaked CO₂. We present the results of a monitoring experiment using seismic field data acquired with
67 ACROSS in the Tokai region, Japan.

68

69 **2. Method**

70 To monitor the shallow subsurface including leaked CO₂, we extracted the time-variation of
71 dispersion curves of Rayleigh waves from vertical components of multichannel seismic data. By
72 applying a simple wavelength conversion to the extracted surface-wave phase velocities, we
73 estimated the depth distribution of the change in S-wave velocities induced by CO₂ leakage. A
74 distinct feature of our continuous monitoring method is the use of seismic energy from ACROSS
75 instead of ambient noise. Previous studies have demonstrated that the source functions of ACROSS
76 can be precisely controlled to enable the detection of small changes in seismic velocity (e.g., Ikuta
77 and Yamaoka, 2004; Ikuta et al., 2002; Yamaoka et al., 2001). The high stability of the ACROSS
78 signals makes it feasible to detect the subtle changes in phase velocities associated with CO₂
79 leakage.

80 In this section, we summarize surface-wave analysis for estimation of dispersion curves of surface
81 waves. We verify the effectiveness of the wavelength-to-depth conversion by a sensitivity analysis of
82 the response of dispersion curves to changes in S-wave velocities.

83

84 *2.1. Phase velocity estimation*

85 The dispersion spectrum of surface waves U can be obtained by multichannel analysis of surface
86 waves (MASW; Park et al., 1999) using the phase shift method (Park et al., 1998) as follows:

87

$$U(c, f) = \left| \int_{-\infty}^{+\infty} \frac{F(x, f)}{|F(x, f)|} e^{i2\pi f x / c(f)} dx \right|, \quad (1)$$

88

89 where c is the phase velocity, f is the frequency, x is the source to receiver distance, and F is a
90 shot gather in the frequency domain. By extracting the phase velocities with maximum amplitude in
91 U for each frequency, dispersion curves of surface waves are determined.

92 In most surface-wave analysis methods, S-wave velocity profiles are obtained by subsequent
93 inversion analysis of extracted dispersion curves (e.g., Xia et al., 1999). Because of the
94 non-uniqueness of surface-wave inversions (e.g., Foti et al., 2009, 2014; Ivanov et al., 2013),
95 however, surface-wave inversion does not yield true S-wave velocity models. The assumption of
96 horizontally layered structures in surface-wave inversion also decreases the accuracy of S-wave
97 velocity estimations. If the time-variation of S-wave velocity is monitored using surface-wave
98 inversion, the results include larger uncertainty than results derived from dispersion curves. For this
99 reason, we prefer to monitor S-wave velocity using dispersion curves without surface-wave
100 inversion.

101

102

103

104 2.2. Sensitivity analysis

105 The relationship between S-wave velocity profiles and dispersion curves is a key part of our analysis,
106 because we interpret the time-variation of S-wave velocity directly from the time-variation of
107 dispersion curves. We therefore performed a sensitivity analysis of the response of dispersion curves
108 to changes in S-wave velocity using a four layered velocity model (Fig. 1a). For simplicity, P-wave
109 velocities and densities of each layer were obtained from S-wave velocities by using empirical
110 equations (Kitsunezaki et al., 1990; Ludwig et al., 1970). The compound matrix method (Saito,
111 1988; Saito and Kabasawa, 1993) was used to compute theoretical dispersion curves of Rayleigh
112 waves. We computed fundamental mode of theoretical dispersion curves for layered models with $\pm$
113 5 % range in S-wave velocities for each layer (Fig. 1a), while holding P-wave velocities and
114 densities fixed because their sensitivity to change in dispersion curves is low (e.g., Xia et al., 1999).
115 To simulate the S-wave velocity change associated with CO₂ leakage from deep reservoirs, we
116 varied S-wave velocities from the fourth layer (a semi-infinite half-space) up to a specified shallower
117 layer. When S-wave velocities were varied in the fourth layer alone, we observed changes in phase
118 velocities at frequencies below 3 Hz (blue and red dashed lines in Fig. 1b). When S-wave velocities
119 were varied in all layers, representing a rise of leaked CO₂ to the surface, we observed changes in
120 phase velocity at wider frequency ranges (cyan and green lines in Fig. 1b).

121 To clarify the frequency-dependent change in phase velocities associated with variation in S-wave
122 velocities, we defined the following indicator of phase velocity change:

123

$$\epsilon(f) = \frac{c(f) - c_B(f)}{c_B(f)} \times 100 \quad (\%), \quad (2)$$

124

125 where c and c_B are the theoretical phase velocities for the models with and without change in
126 S-wave velocities, respectively. The computed ϵ values indicate that, as changes in S-wave
127 velocities reach the surface layer, the change in phase velocities becomes larger and covers a wider
128 frequency range (Fig. 1c). This result suggests that, for the layered model in Fig. 1a, changes in
129 phase velocities at a certain frequency range can be used to estimate changes in S-wave velocities at
130 a corresponding depth range due to CO₂ leakage.

131 In monitoring CO₂ leakage, a vital piece of information is the depth distribution of leaked CO₂.
132 The most sensitive depth on S-wave velocity profiles is often roughly estimated as one-half to
133 one-third of the wavelength derived from the surface-wave phase velocity (e.g., Foti, 2000; Hayashi,
134 2008). In the proposed method, we converted the velocity change indicator ϵ in the frequency
135 domain (Fig. 1c) into one-third wavelength (~depth) domain (Fig. 1d). In the conversion, we used
136 wavelengths from theoretical phase velocities for the model without changing S-wave velocities
137 (black line in Fig. 1b). The converted velocity changes in the depth domain (Fig. 1d) indicate that the

138 one-third wavelength transformation is effective in estimating depth distributions with changes in
139 S-wave velocities. For example, if we observe the change in phase velocities described by the cyan
140 dashed line in Fig. 1c, the corresponding depth distribution can be evaluated as the cyan dashed line
141 in Fig. 1d. Because this case corresponds to variation in S-wave velocities deeper than 5 m, the result
142 from the wavelength conversion is acceptable as a rough estimate for the model in Fig. 1a.
143

144 **3. Numerical simulation for sensitivity analysis**

145 In this section, we describe a numerical simulation of the proposed monitoring method for detection
146 of CO₂ leakage. We synthesized seismic data for 2D velocity models at several stages of CO₂
147 leakage, then estimated the spatial distribution of leaked CO₂ from the change in local phase
148 velocities. The main object of this exercise was to clarify the sensitivity of the method to CO₂
149 leakage in realistic heterogeneous models.

150

151 *3.1. Simulation model*

152 By referring to the models of Shang and Huang (2012), we constructed two 2D models, one
153 including a normal fault zone 10 m wide with a 70° dip angle (Fig. 2a), and the other including a
154 reverse fault zone 10 m wide with a 30° dip angle (Fig. 2c). We assumed 10 m of displacement at
155 each fault zone. We also assumed that S-wave velocities in the fault zones without CO₂ leakage were
156 30 % lower than in the surrounding rock. For simplicity, P-wave velocities and densities were
157 obtained from S-wave velocities by using empirical equations (Kitsunezaki et al., 1990; Ludwig et
158 al., 1970).

Fig. 2. 2D simulation models and synthesized waveforms from sources at 600 m horizontal distance. (a) Model including a normal fault zone with a 70° dip angle without CO₂ leakage. (b) Synthesized waveform of model (a). (c) Model including a reverse fault zone with a 30° dip angle without CO₂ leakage. (d) Synthesized waveform of model (c). We modeled four stages of CO₂

leakage from fault zones (magenta in (a) and (c)) based on the presence of leaked CO₂ at horizontal planes A-C in (a) and (c), and the surface.

159 In the simulation, we assumed that injected CO₂ leaked from deep reservoirs through the fault
160 zones (magenta in Figs. 2a and c). We changed elastic parameters of the fracture zones representing
161 replacement of water filled pore space with leaked CO₂ in gas phase. S-wave velocities in the fault
162 zones were increased by 5 %, whereas densities were decreased by 10 %. The increase in S-wave
163 velocity is reasonable because shear modulus is unchanged and only the decrease in density has an
164 effect on the change in S-wave velocity. For example, if 50 % of pore space is filled with gaseous
165 CO₂, S-wave velocity increases by ~5 % and density decreases by ~10 % (see supplemental material
166 A for details). For simplicity, we assumed P-wave velocities were decreased by 5 %. We modeled
167 four stages of CO₂ leakage, based on the presence of leaked CO₂ at horizontal planes A-C and the
168 surface (Figs. 2a and c).

169 P-SV waves were computed by the finite-difference method using a velocity-stress staggered grid
170 (Virieux, 1986), with an absorbing boundary condition (Cerjan et al., 1985). In field data acquisition
171 using ACROSS, a sweep signal was used as the energy source (see details in Section 4). However,
172 the 50 s modulation period of ACROSS was too long for the numerical simulation, so instead we
173 used a 10 Hz Ricker wavelet as the source function. The frequency spectrum of the 10 Hz Ricker
174 wavelet covers with the source spectrum of the ACROSS we used (Fig.S1). As our monitoring

175 method assumed a fixed seismic source as ACROSS, we used a single source located on the surface
 176 at 600 m horizontal distance. Synthesized waveforms were recorded on the surface at 5 m intervals
 177 (e.g., Figs. 2b and d). Details of the simulations are given as supplemental material B.

178 Because the locations of CO₂ leakage are spatially localized, we need to detect lateral variations of
 179 changes in phase velocities. We defined a subarray composed of fifteen successive receivers and
 180 extracted local dispersion curves for each subarray by the MASW. The spatial variation of phase
 181 velocities was obtained by plotting local phase velocities at the midpoint of each subarray (e.g., Figs.
 182 3a and b).

Fig. 3. (a) and (b) Lateral variations of estimated phase velocities for normal fault models (a)

without CO₂ leakage and (b) with CO₂ leakage from the surface. (c) - (f) Lateral variations of velocity change indicator ϵ when leaked CO₂ reaches (c) the surface and horizontal planes (d) A, (e) B, and (f) C. (g) Lateral variation of velocity change indicator ϵ in the one-third wavelength (~depth) domain when leaked CO₂ reaches horizontal plane A. Phase velocity changes within the black rectangle in (d) are used. The slanting magenta outline represents the CO₂ leakage zone.

183

184 3.2. Normal fault model

185 We extracted clear lateral variations of local phase velocities from the synthesized waveforms for the
186 model that included a normal fault zone, without or with CO₂ leakage (Figs. 3a and b). To estimate
187 the spatial variations of change in phase velocities, we computed lateral variations of the velocity
188 change indicator ϵ by comparing local phase velocities for the models at each stage of CO₂ leakage
189 (Figs 3c-f). When leaked CO₂ reached the surface (Fig. 3c), phase velocities clearly increased around
190 the location of the leakage (~300 m horizontal distance) in the 5-20 Hz frequency range. When
191 leaked CO₂ reached horizontal plane A (5 m from the surface) (Fig. 3d), the change in phase
192 velocities was weaker but still clear. When leaked CO₂ reached plane B or C (Figs. 3e and f), no
193 increase in phase velocities could be distinguished.

194 These results suggest that changes in phase velocities (> 1 % increases) can be observed around
195 the location of CO₂ leakage when leaked CO₂ reaches horizontal plane A (Fig. 3d). To estimate the

196 depth distribution of leaked CO₂ for this case, we converted phase velocity changes in the frequency
197 domain from 5-20 Hz and at 250-400 m horizontal distance range (black rectangle in Fig. 3d) into
198 the one-third wavelength (~depth) domain (Fig. 3g). The wavelength was obtained from the
199 estimated local phase velocities for the model without CO₂ leakage (Fig. 3a). Local phase velocities
200 with increases greater than 1 % were distributed around the CO₂ leakage zone in the depth range
201 between approximately 10 and 50 m (Fig. 3g). The shallower boundary is roughly consistent with
202 the 5 m depth limit of CO₂ leakage. The area of increased phase velocity was wider than the 10 m
203 width of the fault zone because each local phase velocity was extracted from the subarray with a 70
204 m receiver spread.

205

206 3.3. Reverse fault model

207 We extracted clear lateral variations of local phase velocities from the synthesized waveforms for the
208 model that included a reverse fault zone (Figs. 4a and b). When leaked CO₂ reached the surface (Fig.
209 4c), we observed a clear increase of phase velocities around the location of the leakage (~350 m
210 horizontal distance) in the 5-20 Hz frequency range. However, we also observed large fluctuations in
211 the change of phase velocities at < 300 m horizontal distance in the 5-10 Hz frequency range at this
212 and other stages of CO₂ leakage (Figs. 4c-e). These fluctuations appear to be caused by instable
213 phase velocity estimation, as we observed instability (discontinuity) in the estimated local phase

214 velocities due to scattering effects from lateral heterogeneity of the simulated models (Figs. 4a and
 215 b). When leaked CO₂ reached horizontal plane A (Fig. 4d), the increase of phase velocities around
 216 350 m horizontal distance was still apparent in the 5-10 Hz frequency range. When leaked CO₂
 217 reached plane B or C (Figs. 4e and f), no changes in phase velocity could be distinguished.

218 The fluctuations in the 5-10 Hz range at < 300 m horizontal distance might interfere with
 219 identifying the location of CO₂ leakage. To suppress this interference, we performed a similar
 220 time-lapse analysis for a source on the opposite side of the fault zone (at 0 m horizontal distance)

221 and observed smooth lateral variations in phase velocities at < 300 m horizontal distance (Figs. 5a
 222 and b). When leaked CO₂ reached the surface or horizontal plane A (Figs. 5c and d), we observed a
 223 clear increase of local phase velocities around 350 m horizontal distance, as was the case with the
 224 source on the opposite side. The area with increased phase velocities was curved slightly to the left
 225 side at ~5 Hz, reflecting the dip angle of the fault zone. The spurious change at < 300 m horizontal
 226 distance disappeared, but similar fluctuations appeared on the opposite side (> 300 m horizontal
 227 distance in Figs. 5c-e).

Fig. 5. Same as Fig. 4 except that the source is located at 0 m horizontal distance.

228 From the results of both source cases, we could distinguish $> 1\%$ increases in phase velocities
229 around the location of leakage from spurious changes at other locations. As a result, the site of CO_2
230 leakage could be located whenever it reached horizontal plane A (Figs. 4d and 5d). To estimate the
231 depth distribution of leaked CO_2 for these cases, we converted the change in phase velocities in the
232 5-20 Hz frequency range and 250-400 m horizontal distance range (black rectangles in Figs. 4d and
233 5d) into the one-third wavelength domain (Figs. 4g and 5g). In both source cases, we observed areas
234 with $> 1\%$ phase velocity increase between 300 and 350 m horizontal distance. Although the low
235 dip angle of the fault was not retrieved when the source was on the right-hand side of the fault (Fig.
236 4g), we observed an appropriate slope when the source was on the left-hand side (Fig. 5g). The area
237 with $> 1\%$ increase in phase velocity was wider than the fault zone owing to the receiver spread.
238 The shallower boundaries of the area of increased phase velocities were ~ 10 m deep, an acceptable
239 approximation of the 5 m depth limit of CO_2 leakage.

240 Our simulation study of two different heterogeneous models indicates that the spatial distribution
241 of leaked CO_2 can be detected as temporal change in phase velocities ranged from ~ 1 -3 % increases.
242 In other words, detecting CO_2 leakage by the proposed method requires us to monitor the
243 time-variation of phase velocities with better than 1 % accuracy.

244

245 **4. Application for field data**

246 In this section, we describe a feasibility test of the proposed monitoring method using field data
247 continuously acquired with ACROSS. Although the site is not a CO₂ storage site, it is located near a
248 busy road. There were no events during data acquisition, such as a large earthquake or rainfall event
249 that would cause changes in the subsurface velocity; therefore the site was suitable for testing the
250 time-stability of our method in noisy conditions.

251

252 *4.1. Data*

253 We used seismic data acquired on 5-6 August 2014 by an ACROSS unit installed at the Toyohashi
254 site in the Tokai region of Japan (Fig. 6) (Yamaoka et al., 2014). The ACROSS was operated with a
255 sweep frequency range of 5.015-15.015 Hz and a 0.02 Hz interval. The rotational axis of the
256 ACROSS unit was horizontal, and the rotation direction was switched every hour. A linear vibration
257 in any direction could be synthesized from a combination of clockwise and anticlockwise rotations
258 (e.g., Saiga et al., 2006; Yamaoka et al., 2014). We synthesized a vibration of the ACROSS for a
259 vertical direction. Eight geophones with 4.5 Hz natural frequency were used for receivers. These
260 were aligned with ~10 m spacing on a farm road (Fig. 6) and operated with a sampling interval of 5
261 ms. We used the vertical component of 14 hours of continuous seismic records and synthesized
262 transfer functions of the ACROSS unit for a vertical force.

263

264 4.2. Transfer function of ACROSS

265 We divided each hour of ACROSS data into nine segments of 400 s (Figs. 7a and b). We stacked the

266 first eight segments in the frequency domain, ignoring the data for the last segment because it

267 contained a spin-down and a spin-up period when the ACROSS unit reversed its direction of rotation.

268 Since the modulation period of the ACROSS was 50 s and eight cycles were included in our 400 s

269 time window, estimated amplitude spectra had much larger amplitude every eight data points in the

frequency domain (red in Figs. 7c and d), representing signals from the ACROSS, whereas other data points corresponded to the noise (Maeda et al., 2015; black in Figs. 7c and d).

Fig. 7. Examples of a 400 s time window of observed seismic data (a) at receiver N and (b) at receiver F; locations in Fig. 6b. Examples of spectra obtained by stacking eight segments (c) at receiver N and (d) at receiver F. Red lines represent signals from the ACROSS. Note that the data outside the frequency range of the FM operation of the ACROSS are also colored in red with the same frequency interval.

We computed 13 transfer functions of the ACROSS unit by using each successive 2-hour dataset so as to include both clockwise and anticlockwise rotations (Fig. 8). Transfer functions in time domain were obtained by applying inverse Fourier transform for stacked data in the frequency range of the ACROSS operation. Dispersive surface waves were dominant in the stacked transfer functions (Fig. 9a). Time-variations of each transfer function obtained from each 2-hour dataset showed high repeatability and S/N ratios during the data observation period (Figs. 9b and c).

Fig. 9. (a) Transfer functions of the ACROSS data obtained from 14-hours of data. Red dashed lines indicate the traveltimes of waves with 600 and 200 m/s. (b, c) Time variations of transfer functions obtained from successive pairs of 2-hour datasets at receivers N and F, respectively. Amplitudes in (b) and (c) are normalized by the maximum absolute value in each panel.

Time-lapse data are plotted at the midpoints of each stacked period.

278

279 4.3. Results

280 4.3.1. Phase velocity estimation

281 We extracted a dispersion curve for surface waves by applying the MASW for the transfer function
282 obtained from the first 2-hour dataset from eight receivers (Fig. 10a). When stacking each segment,
283 the data in the frequency domain were normalized by the amplitude so as to stack only phase
284 information. In the frequency range of the ACROSS signals (5.015 – 15.015 Hz), we clearly
285 observed surface-wave phase velocities. In the 5-9 Hz frequency range, we observed an abrupt
286 increase in phase velocities as the frequency decreased, probably reflecting a strong contrast in
287 S-wave velocity between a sedimentary layer and bedrock. Since the source signal of the ACROSS
288 is generated by a centrifugal force of an eccentric mass, a source force is proportional to the square
289 of the rotational frequency (e.g., Yamaoka et al., 2014; Fig.S1). This makes the source force at lower
290 frequencies weak as we observed scattering in the estimated phase velocities at lower frequencies
291 (5-8 Hz). A high-pass filter effect imposed by the medium on surface waves (e.g., Scherbaum et al.,
292 2003) would be also responsible for instability of phase velocity estimation at lower frequencies.

Fig. 10. Dispersion curves estimated from (a) 2-hours of data and (b) 14-hours of data in the frequency range 2.015 – 24.995 Hz at 0.02 Hz intervals. Red dots represent phase velocities with maximum amplitude for each frequency. Green crosses represent phase velocities from surface-wave exploration using a sledgehammer (Watanabe et al., 2007). Background shade represents the dispersion spectrum normalized by the number of receivers.

293 To improve the accuracy of the phase velocity estimation, we stacked all 13 transfer functions (14
 294 hours of data) and extracted the dispersion curve (Fig. 10b). By increasing the stacking time, we
 295 obtained smoother (more reliable) phase velocities in the 5-8 Hz frequency range. A higher mode of
 296 surface waves appeared at ~25 Hz, a frequency range within the overtone of ACROSS energy.

297 Figure 10 compares the phase velocities estimated with ACROSS to those estimated from
 298 surface-wave exploration using a sledgehammer (Watanabe et al., 2007). Both phase velocities
 299 coincided in the 9-15 Hz frequency range. Below 9 Hz, however, the phase velocities estimated with
 300 a sledgehammer had much lower phase velocities. This is probably because, at low frequencies,
 301 surface waves with sufficient energy were difficult to excite by a sledgehammer. One may exclude

302 the phase velocities obtained with the sledgehammer below 9 Hz.

303

304 4.3.2. *The effect of stacking time on phase velocity estimation*

305 The estimated dispersion curves shown in Fig. 10 indicate that the stability of phase velocity
306 estimates depends on stacking time (S/N ratio) at each frequency. To explore the effect of stacking
307 time on phase velocity estimates, we extracted phase velocities with respect to stacking time (2-14
308 hours of data) and compared phase velocities estimated from different stacking times by the
309 following indicator of phase velocity variation:

310

$$v_m(f) = \frac{c_m(f) - c_{14}(f)}{c_{14}(f)} \times 100 \quad (\%), \quad (3)$$

311

312 where c_m and c_{14} are the phase velocities estimated from the first m hours of data and all 14 hours
313 of data, respectively. Figure 11 shows that at lower frequencies, the longer period requires more time
314 for each cycle to obtain stable estimates of phase velocity. In the 10-15 Hz frequency range, however,
315 the velocity variation was less than 1 % even with only 2 hours of data.

Fig. 11. Velocity variation of phase velocities with respect to stacking time (2-13 hours of data) for phase velocities obtained using all 14 hours of data, computed by Eq. (3).

316

317 4.3.3. Time-variation of phase velocity

318 We applied the MASW to transfer functions obtained from each 2 hours of data. The observed
319 time-variation shows high repeatability of phase velocity estimation (Fig. 12a). To obtain the
320 time-variation of phase velocities, we defined the following velocity change indicator:

321

$$\epsilon_k(f) = \frac{c_k(f) - c_{ave}(f)}{c_{ave}(f)} \times 100 \text{ (\%)}, \quad (4)$$

322

323 where c_k is the phase velocity estimated from the k th transfer function of 2-hour data and c_{ave}

324 is the average of the estimated phase velocities over all time-lapse pairs. In the 10-15 Hz frequency

range, the time-variation of change in the estimated phase velocities was very small ($< 1\%$) (Figs. 12b and c). At frequencies below 10 Hz, the estimated phase velocities varied greater than 5 % due to the low S/N ratios of surface waves at low frequencies.

Fig. 12. Time variations of (a) phase velocities estimated from each 2-hour dataset and (b, c) velocity change for mean phase velocities computed by Eq. (4) with two different color scales. Time-lapse data are plotted at the midpoints of each stacked period.

To improve the time-stability of phase velocity estimates, we extracted the time-variation of phase

329 velocities from each 6 hours of data (Fig. 13). As shown in Fig. 11, increasing stacking time reduced
 330 the time-variation of phase velocities. At frequencies below 10 Hz, however, more stacking time was
 331 required to monitor phase velocities with better than 1 % accuracy.

332 4.3.4. Lateral variation of time-lapse analysis

333 To analyze the lateral resolution of our time-lapse analysis, we divided the eight receivers into two
 334 subarrays (Fig. 6b) and extracted the time-variation of phase velocities for each subarray using each
 335 2-hour dataset (Fig. 14). The estimated phase velocities differed in two subarrays. Compared to the
 336 case using eight receivers (Fig. 12), the phase velocity estimates were less stable because we used
 337 fewer receivers. Nevertheless, we observed highly stable time-variation of phase velocities ($\sim 1\%$) in
 338 the 10-15 Hz range. We reduced the time-variation of phase velocities by performing similar
 339 time-lapse analyses using each 6-hour data period (Fig. 15).

Fig. 14. Time variations of (a) phase velocities estimated from each 2-hour dataset using subarray 1, (b) velocity change for mean phase velocities of (a), (c) phase velocities estimated from 2-hour dataset using subarray 2, and (d) velocity change for mean phase velocities of (c). Time-lapse data are plotted at the midpoints of each stacked period.

Fig. 15. Time variations of (a) phase velocities estimated from each 6-hour dataset using subarray 1, (b) velocity change for mean phase velocities of (a), (c) phase velocities estimated from each 6-hour dataset using subarray 2, and (d) velocity change for mean phase velocities of (c). Time-lapse data are plotted at the midpoints of each stacked period.

340 Our time-lapse surface-wave analysis with ACROSS data was successful in documenting very

341 small time-variation of phase velocities ($< 1\%$) in the 10-15 Hz frequency range. According to

342 one-third wavelength transformation, the corresponding depth is ranged from 8-14 m.

343 **5. Discussion**

344 Our field data analysis shows that we can successfully monitor the time-variation of phase velocities
345 with better than 1 % accuracy from field data acquired with ACROSS in a noisy situation. Our
346 numerical simulation of CO₂ leakage shows that this time-stability is sufficient for detecting small
347 changes in phase velocities (~1-3 %) associated with CO₂ leakage. Considering one-third
348 wavelength of the phase velocities estimated from field data, our approach has potential to identify
349 leaked CO₂ when reaching ~ 10 m deep from the surface.

350 In our field example, we observed clear lateral variations of phase velocities using two sets of
351 subarrays, reflecting lateral heterogeneity. However, the lateral resolution was low because only one
352 ACROSS unit and eight receivers were used. The number of ACROSS units we can install in a
353 particular area is limited owing to their cost or spatial requirements to install ACROSS units. In our
354 method, therefore, good horizontal resolution in locating CO₂ leakage requires a large number of
355 receivers on the surface. Receiver arrays are frequently installed in CO₂ storage sites for
356 microseismic monitoring. If these arrays can provide the resolution required for monitoring the
357 shallow subsurface, we can make use of previously installed arrays.

358 In monitoring studies using ambient noise correlations, Brenguier et al. (2008a, 2008b and 2014)
359 and Clarke et al. (2011) demonstrated that temporal-variations of seismic velocity as small as 0.1 %
360 could be monitored by the Moving Window Cross-Spectral technique (MWCS; Poupinet et al.,

1984). Compared to the MASW we used for phase velocity estimation, the MWCS technique can extract small change in seismic velocity without the use of receiver arrays, indicating high lateral resolution of the MWCS. However, the MWCS can extract only relative change in velocity (or delay time) rather than the values of velocity. As we demonstrated using the MASW, the values of phase velocity are required to estimate depth distribution of change in S-wave velocity. The MWCS also requires the assumption of constant delay time within the frequency range of interest in each moving window. This decreases frequency resolution when analyzing frequency-dependent surface-waves.

Installing a second ACROSS unit on the opposite side of the target site can improve subsurface monitoring by our method. Our simulation study including dipping faults showed that additional ACROSS data from the opposite direction would allow us to distinguish spurious change in phase velocities due to scattering from change in phase velocities around locations of CO₂ leakage. By using slightly different carrier frequencies, transfer functions of multiple ACROSS units can be monitored simultaneously (e.g., Takanashi et al., 2014).

Several studies using ACROSS have shown that temporal changes in its transfer functions may be caused by changes in near-surface conditions such as atmospheric temperature or rainfall (e.g., Saiga, et al., 2006; Takanashi et al., 2014). By using correlations of ambient seismic noise, Meier et al. (2010) observed seasonal variations in seismic velocities. In the time-lapse results obtained from field seismic data, we observed temporal-variations of phase velocity. In particular, the estimated

379 phase velocities above ~8 Hz show systematic temporal-variations with the boundaries around 2:00
380 a.m. on 6 August (Figs. 13c, 15b and d). However, the observed variations are difficult to interpret
381 by natural effects because there were no rainfall events during data acquisition, and the variations
382 show opposite trend in two subarrays (Figs 15b and d). Longer continuous seismic data is required to
383 discuss the causes of velocity variations in the study field.

384 In monitoring CO₂ leakage, near-surface velocity variations due to natural phenomena may mask
385 velocity variations due to CO₂ leakage. To distinguish both velocity variations, we need to
386 investigate sensitivity of our monitoring method to natural effects before injecting CO₂. If such
387 near-surface effects due to natural phenomena can be identified and corrected, it can contribute to
388 monitoring not only the shallow subsurface, but also deep reservoirs because near-surface structures
389 influence deep reflections. Our method using surface waves can easily focus on time-variation of
390 transfer functions in the shallow subsurface, and therefore has high potential in evaluating
391 near-surface effects for improving monitoring deep subsurface.

392

393 **6. Conclusions**

394 To detect CO₂ leakage in the shallow subsurface, we described a monitoring method using
395 surface-wave analysis with ACROSS technology. Our numerical simulation demonstrated that the
396 spatial distribution of leaked CO₂ through fault zones can be detected as small (~1-3 %)
397 temporal-variation of surface-wave phase velocities. In our analysis of continuous seismic records

398 acquired with ACROSS, we extracted clear dispersion curves of surface waves in the frequency
399 range produced by ACROSS. In particular, we made reliable estimates of phase velocities in the
400 10-15 Hz frequency range that agreed with the result of surface-wave exploration using a
401 sledgehammer energy source. The time-variation of the estimated phase velocities was better than
402 1% accuracy even when the time-lapse estimates were based on successive 2-hour dataset. These
403 results show that our monitoring method has the capability to detect change in phase velocities
404 associated with CO₂ leakage.

405

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414

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522

523

524

525 **Figure Captions**

526 **Fig. 1.** (a) Four-layered S-wave model with gray shading representing 5 % variation in S-wave
527 velocity. (b) Theoretical dispersion curves for the four-layered model (black) and for the
528 models with changed S-wave velocities in various layers (colors). (c) Velocity change
529 indicator ϵ for each model computed by Eq. (2). (d) Velocity change indicator ϵ in the
530 one-third wavelength ($\sim$ depth) domain. Gray shading represents velocity changes within a
531 5 % range; dashed black lines represent boundaries of model layers.

532

533 **Fig. 2.** 2D simulation models and synthesized waveforms from sources at 600 m horizontal distance.
534 (a) Model including a normal fault zone with a 70° dip angle without CO₂ leakage. (b)
535 Synthesized waveform of model (a). (c) Model including a reverse fault zone with a 30° dip
536 angle without CO₂ leakage. (d) Synthesized waveform of model (c). We modeled four stages
537 of CO₂ leakage from fault zones (magenta in (a) and (c)) based on the presence of leaked
538 CO₂ at horizontal planes A - C in (a) and (c), and the surface.

539

540 **Fig. 3.** (a) and (b) Lateral variations of estimated phase velocities for normal fault models (a)
541 without CO₂ leakage and (b) with CO₂ leakage from the surface. (c) - (f) Lateral variations
542 of velocity change indicator ϵ when leaked CO₂ reaches (c) the surface and horizontal

543 planes (d) A, (e) B, and (f) C. (g) Lateral variation of velocity change indicator ϵ in the
544 one-third wavelength ($\sim$ depth) domain when leaked CO₂ reaches horizontal plane A. Phase
545 velocity changes within the black rectangle in (d) are used. The slanting magenta outline
546 represents the CO₂ leakage zone.

547

548 **Fig. 4.** Lateral variations of estimated phase velocities and ϵ for reverse fault models. Explanation
549 is the same as in Fig.3.

550

551 **Fig. 5.** Same as Fig. 4 except that the source is located at 0 m horizontal distance.

552

553 **Fig. 6.** (a) Location of the ACROSS unit (star), and the survey line (red). Geospatial Information
554 Authority of Japan (GSI) map was used for this panel. (b) Detailed arrangement of the
555 ACROSS unit and receiver array.

556

557 **Fig. 7.** Examples of a 400 s time window of observed seismic data (a) at receiver N and (b) at
558 receiver F; locations in Fig. 6b. Examples of spectra obtained by stacking eight segments (c)
559 at receiver N and (d) at receiver F. Red lines represent signals from the ACROSS. Note that
560 the data outside the frequency range of the FM operation of the ACROSS are also colored in

561 red with the same frequency interval.

562

563 **Fig. 8.** Schematic diagram showing the definition of transfer functions in the time sequence of the

564 ACROSS data. The origin corresponds to 7:00 p.m. on 5 August 2014.

565

566 **Fig. 9.** (a) Transfer functions of the ACROSS data obtained from 14-hours of data. Red dashed lines

567 indicate the traveltimes of waves with 600 and 200 m/s. (b, c) Time variations of transfer

568 functions obtained from successive pairs of 2-hour datasets at receivers N and F, respectively.

569 Amplitudes in (b) and (c) are normalized by the maximum absolute value in each panel.

570 Time-lapse data are plotted at the midpoints of each stacked period.

571

572 **Fig. 10.** Dispersion curves estimated from (a) 2-hours of data and (b) 14-hours of data in the

573 frequency range 2.015 – 24.995 Hz at 0.02 Hz intervals. Red dots represent phase velocities

574 with maximum amplitude for each frequency. Green crosses represent phase velocities from

575 surface-wave exploration using a sledgehammer (Watanabe et al., 2007). Background shade

576 represents the dispersion spectrum normalized by the number of receivers.

577

578 **Fig. 11.** Velocity variation of phase velocities with respect to stacking time (2-13 hours of data) for

579 phase velocities obtained using all 14 hours of data, computed by Eq. (3).

580

581 **Fig. 12.** Time variations of (a) phase velocities estimated from each 2-hour dataset and (b, c)

582 velocity change for mean phase velocities computed by Eq. (4) with two different color

583 scales. Time-lapse data are plotted at the midpoints of each stacked period.

584

585 **Fig. 13.** Time variations of (a) phase velocities estimated from each 6-hour dataset and (b, c)

586 velocity change for mean phase velocities with two different color scales. Time-lapse data

587 are plotted at the midpoints of each stacked period.

588

589 **Fig. 14.** Time variations of (a) phase velocities estimated from each 2-hour dataset using subarray 1,

590 (b) velocity change for mean phase velocities of (a), (c) phase velocities estimated from

591 2-hour dataset using subarray 2, and (d) velocity change for mean phase velocities of (c).

592 Time-lapse data are plotted at the midpoints of each stacked period.

593

594 **Fig. 15.** Time variations of (a) phase velocities estimated from each 6-hour dataset using subarray 1,

595 (b) velocity change for mean phase velocities of (a), (c) phase velocities estimated from

596 each 6-hour dataset using subarray 2, and (d) velocity change for mean phase velocities of

597

(c). Time-lapse data are plotted at the midpoints of each stacked period.

598