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## Effects of Nonlinear Soil Behavior on Kappa ( $\kappa$ ): Observations from the KiK-Net Database

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► **To cite this version:**

Chunyang Ji, Ashly Cabas, Luis Fabian Bonilla, Céline Gelis. Effects of Nonlinear Soil Behavior on Kappa ( $\kappa$ ): Observations from the KiK-Net Database. Bulletin of the Seismological Society of America, 2021, 111 (4), pp.2138 - 2157. 10.1785/0120200286 . hal-04402168v2

**HAL Id: hal-04402168**

**<https://univ-eiffel.hal.science/hal-04402168v2>**

Submitted on 30 Jan 2024

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1     **Effects of Nonlinear Soil Behavior on Kappa ( $\kappa$ ): Observations from the KiK-net**  
2                                   **database**

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5     **Declaration of competing interests**

6     The authors acknowledge there are no conflicts of interest recorded.  
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## Abstract

22  
23 Soil nonlinear behavior is often triggered in soft sedimentary deposits subjected to strong ground  
24 shaking and has led to catastrophic damage to civil infrastructure in many past earthquakes.  
25 Nonlinear behavior in soils is associated with large shear strains, increased material damping ratio  
26 and reduced stiffness. However, most investigations of the high-frequency spectral decay  
27 parameter  $\kappa$ , which captures attenuation, have focused on low-intensity ground motions inducing  
28 only small shear strains. Because studies of the applicability of the  $\kappa$ -model when larger  
29 deformations are induced are limited, this paper investigates the behavior of  $\kappa$  (both  $\kappa_r$  per record  
30 and site-specific  $\kappa_0$  estimates) beyond the linear-elastic regime. Twenty stations from the KiK-net  
31 database, with time-average shear wave velocities in the upper 30 m between 213 and 626 m/s, are  
32 used in this study. We find that the classification scheme used to identify ground motions that  
33 trigger soil nonlinear behavior biases estimates of  $\kappa_0$  in the linear and nonlinear regimes. A hybrid  
34 method to overcome such bias is proposed considering proxies for in situ deformation (via the  
35 shear strain index) and ground shaking intensity (via peak ground acceleration). Our findings show  
36 that soil nonlinearity affects  $\kappa_r$  and  $\kappa_0$  estimates, but this influence is station-dependent. Most  $\kappa_0$   
37 at our sites had a 5-20% increase at the onset of soil nonlinear behavior. Velocity gradients and  
38 impedance contrasts influence the degree of soil nonlinearity and its effects on  $\kappa_r$  and  $\kappa_0$ . Moreover,  
39 we observe that other complexities in the wave propagation phenomenon (e.g., scattering and  
40 amplifications in the high-frequency range) impose challenges to the application of the  $\kappa_0$ -model,  
41 including the estimation of negative values of  $\kappa_r$ .

42

## Introduction

43  
44 The anelastic attenuation of seismic waves as they travel through sedimentary deposits is a  
45 function of the deformations induced, which in turn depend on the material properties (e.g.,  
46 plasticity of the soil) and the intensity of the ground shaking. Material damping ratio,  $\xi$ , is  
47 commonly used in geotechnical earthquake engineering to quantify viscous and anelastic energy  
48 dissipation in soils subjected to dynamic loading. Empirical models of  $\xi$  often have a constant  
49 minimum value (known as the minimum shear-strain damping,  $\xi_{\min}$ ) for small shear strains  
50 considered in the linear-elastic regime (e.g., Darendeli, 2001). Yet, values of  $\xi$  increase as larger  
51 shear strains are induced in soil deposits by stronger ground excitations (Idriss et al. 1978, Seed et  
52 al. 1986, Darendeli 2001). The characterization of  $\xi$  across a wide range of strains is essential to  
53 model the effects of local soil conditions on earthquake ground motions.

54  
55 The high-frequency spectral decay parameter  $\kappa$  was introduced by Anderson and Hough (1984)  
56 based on the Fourier spectrum characteristics of a ground motion's shear-wave window recorded  
57 directly in the field, which makes it an observable parameter that quantifies total attenuation (e.g.,  
58 energy dissipation caused by scattering and anelasticity). Estimates of  $\kappa$  have proven useful in  
59 multiple applications, from stochastic modeling of ground motions (Boore 2003) to the  
60 development of host-to-target adjustments of ground motion models (e.g., Campbell 2003, Al Atik  
61 et al. 2014). The site-specific, distance-independent component of  $\kappa$ , known as  $\kappa_0$  (Anderson 1991),  
62 is defined as a site parameter that captures the attenuation due to the propagation of seismic waves  
63 through near-surface materials. The relationship between  $\kappa_0$  and  $\xi_{\min}$  has been investigated in  
64 previous studies (e.g., Cabas et al. 2017; Ktenidou et al. 2015; Xu et al. 2019) for weak motion  
65 data, but the quantification of  $\kappa$  and  $\kappa_0$  beyond the linear-elastic regime remains unsolved.

66

67 Most studies on individual estimates of  $\kappa$  (i.e., the value measured from the observed Fourier  
68 Amplitude Spectra (FAS) per record following the Anderson and Hough (1984) approach),  
69 hereafter referred to as  $\kappa_r$ , and its site-specific component  $\kappa_0$  have used ground motion records that  
70 do not trigger nonlinear behavior at the sites of interest or that are not considered influenced by  
71 the site's nonlinear response (e.g., Ktenidou et al. 2013, Van Houtte et al. 2011, Laurendeau et al.  
72 2013, Edwards et al. 2015, Perron et al. 2017, Xu et al. 2019). However, nonlinear soil behavior  
73 has often been responsible for increasing the damage potential of strong ground motions in past  
74 earthquakes (e.g., Darragh and Shakal, 1991, Trifunac and Todorovska, 1994, Bonilla et al., 2011,  
75 Rong et al., 2016). Understanding near-surface attenuation effects in the nonlinear regime is then  
76 necessary for a thorough assessment of seismic hazards and risks imposed to civil infrastructure  
77 (Anderson and Hough 1984). Hence, this paper investigates the relationships among  $\kappa$ , shear  
78 strains and ground motion intensity to understand the behavior of  $\kappa$  at the onset of nonlinear soil  
79 behavior.

80

81

## Background

82 The first paper that attempted to connect soils' nonlinear response and  $\kappa_r$  was conducted by Yu et  
83 al. (1992), where the authors compared two simulated records: one from a linear site response  
84 analysis, and the other from a time-domain nonlinear site response analysis. Yu et al. (1992)  
85 observed that the value of  $\kappa_r$  estimated with the Anderson and Hough (1984) approach and  
86 corresponding to the motion affected by soil nonlinearity was smaller. However, later studies  
87 found a positive correlation between  $\kappa_r$  (and  $\kappa_0$ ), strain amplitudes and the intensity of ground  
88 shaking (e.g., Durward et al 1996; Lacave-Lachet et al 2000; Dimitriu et al. 2001).

89

90 Durward et al. (1996) found that  $\kappa_r$  values were a function of peak ground velocity (PGV, varying  
91 from 0.01 to 1 m/s), which was used as a proxy for deformation. Values of  $\kappa_r$  were computed for  
92 more than 60 records observed at 23 sites in the Imperial Valley, California based on the  
93 acceleration spectrum approach (Anderson and Hough, 1984). Durward et al. (1996) hypothesized  
94 that soil nonlinearity had affected  $\kappa_r$  because higher  $\kappa_r$  values correlated well with higher PGVs.  
95 Moreover, Lacave-Lachet et al. (2000) analyzed ground motions from the 1995 Kobe earthquake  
96 in Japan (i.e., the main shock and aftershocks), and found that  $\kappa_r$  values increased with increasing  
97 peak ground acceleration (PGA). Hence, Lacave-Lachet et al. (2000) proposed to use  $\kappa_r$  to detect  
98 the onset of soil nonlinearity. Dimitriu et al. (2001) investigated the dependency between site-  
99 specific  $\kappa_0$  and ground shaking intensity. Values of  $\kappa_r$  for 23 ground motions (i.e., 46 horizontal  
100 components with values of  $\kappa_r$  reported for each individual component) were computed at two  
101 adjacent sites in Lefkas, western Greece, based on the acceleration spectrum method. Dimitriu et  
102 al. (2001) provided evidence that  $\kappa_0$  was a proxy for soil nonlinearity based on the observed  
103 dependency between  $\kappa_0$  and ground shaking amplitudes, which were represented by mean  
104 horizontal acceleration in the S-wave window (MGA), PGA, and PGV. Positive correlations were  
105 found between the 46  $\kappa_0$  values and MGA, PGA, and PGV in log-scale, while a negative  
106 correlation was observed between  $\kappa_0$  and the site dominant-resonance frequency. However, Van  
107 Houtte et al. (2014) identified an opposite correlation between estimates of  $\kappa_0$  (computed as the  
108 individual measured  $\kappa_r$  with epicentral distance less than 30 m) and PGA at hard sites (i.e., with  
109  $V_{s30}$  varying from 422 to 1073 m/s) using ground motions from the 2010-2011 Canterbury  
110 earthquake sequence in New Zealand. The authors suggested further investigations to understand  
111 the associated physical mechanism.

112

113 There are still few and contradicting observations of the effects of nonlinearity on  $\kappa_r$  and  $\kappa_0$   
114 estimates (Ktenidou et al. 2015). Previous studies only considered a very limited database of  
115 ground motions. This paper takes advantage of the unique Japanese Kiban-Kyoshin network (KiK-  
116 net), which is rich in high-quality ground motions, to further investigate the effects of soil  
117 nonlinearity on  $\kappa_r$  and  $\kappa_0$ . More specifically, we explore the dependence of  $\kappa_r$  and  $\kappa_0$  on ground  
118 shaking intensity (i.e., weak, moderate or strong ground motions as parameterized by PGA), and  
119 on the level of shear strains induced in near-surface materials at 20 KiK-net stations. First, we  
120 present the conceptual basis for the relationship between  $\kappa$ , shear strains and ground motion  
121 intensity. Then, we describe our database and methods, starting with the identification of an  
122 appropriate classification scheme for linear and nonlinear ground motions. The analysis of the  
123 effects of ground shaking amplitudes on  $\kappa_r$  at each study site follows. Lastly, we compare the ratio  
124 of nonlinear and linear site-specific  $\kappa_0$  across all selected stations to assess the variation of near-  
125 surface attenuation estimates from the linear-elastic to the nonlinear regime.

126

### 127 **Conceptual basis for the interpretation of $\kappa$ beyond the linear-elastic regime**

128 The induced strain level in a given soil layer is a function of the material properties, and the  
129 amplitude and frequency content of the incoming wavefield at the site. Stronger ground shaking  
130 results in larger-strain responses, which produce an increase in material damping ratio (in  
131 combination with a reduction of shear modulus). The short wavelength of high frequency waves  
132 allows for multiple cycles of shearing in near-surface sedimentary layers, which makes them more  
133 sensitive to the effects of a higher material damping ratio. Thus, we hypothesize that stronger

134 ground shaking inducing larger deformations in sedimentary deposits will affect estimates of the  
135 high-frequency spectral decay parameter  $\kappa$ .

136

137 Figure 1 serves as an example to illustrate this hypothesis. The acceleration FAS and empirical  
138 transfer function (ETF) corresponding to a pair of ground motions recorded at depth and at the  
139 ground surface at FKSH14 are shown. FKSH14 is one of the 20 KiK-net station analyzed in this  
140 work (see Database description). One of the ground motion pairs has a low ground shaking  
141 intensity (with a surface PGA of less than  $0.1 \text{ m/s}^2$  for both horizontal components), while the  
142 other one has a higher ground shaking intensity (with a surface PGA of  $0.71 \text{ m/s}^2$  and  $0.25 \text{ m/s}^2$   
143 for the  $H_1$  and  $H_2$  components, respectively). Values of  $\kappa_r$  per record are also estimated for both  
144 pairs. To minimize the bias from path effects and isolate local site effects on  $\kappa_r$  values per record,  
145 the selected weak and strong ground motions in Figure 1 correspond to events with similar focal  
146 depths, azimuths and epicentral distances (i.e., the focal depths, azimuths and epicentral distances  
147 are 5 km,  $319^\circ$ , and 15.04 km, respectively for the low-intensity event, and 5 km,  $323^\circ$ , and 15.79  
148 km, respectively for the high-intensity event). The moment magnitudes of the events associated  
149 with the weak and strong ground motions in Figure 1 are 4.0 and 5.1, respectively. To reduce the  
150 variability associated with the calculation of  $\kappa_r$  from the acceleration spectrum method, we use the  
151 same frequency window for all ground motions (Edwards et al. 2011).

152

153 Larger values of  $\kappa_r$  at the ground surface (e.g., 0.071 s for the horizontal component  $H_1$ ) are  
154 obtained for the high-intensity ground motion compared to the corresponding  $\kappa_r$  values for the  
155 low-intensity ground motion (e.g., 0.057 s for  $H_1$ ). Likewise, the high-intensity ground motion  
156 results in a larger  $\kappa_{TF}$  (Drouet et al. 2010), which is computed on the decaying portion of the



157 empirical transfer function at high frequencies and is equivalent to  $\Delta\kappa$  (i.e.,  $\kappa_{r\_sur} - \kappa_{r\_bor}$ ) estimates  
158 when using the same frequency band for calculation purposes. The value of  $\kappa_{TF}$  corresponding to  
159 the high-intensity and low-intensity motions are 0.026 s and 0.019 s, respectively. Meanwhile, the  
160 ETF corresponding to the high-intensity event shows lower amplifications at higher frequencies  
161 (e.g., amplification ranges from 1 to 2 between 15 and 30 Hz for  $H_1$  approximately) than its  
162 counterpart for the low-intensity ground motion (i.e., amplification ranges from 2 to 3 between 15  
163 and 30 Hz for  $H_1$  approximately), which reflects the stronger influence of increased material  
164 damping ratio on high frequencies.

165  
166 Values of  $\kappa_r$  and  $\Delta\kappa$  (or  $\kappa_{TF}$  in Figure 1) are identical for the high- and low-intensity records for  
167 the  $H_2$  component. It must be noted that the difference in PGA between the low- and high- intensity  
168 surface ground motions is less significant for the  $H_2$  components than that for the  $H_1$  components,  
169 while the PGAs at depth are very similar (i.e., the borehole PGAs for the high-intensity motion are  
170 0.06 and 0.07  $m/s^2$  for  $H_1$  and  $H_2$  components, respectively; the borehole PGAs for the low-  
171 intensity motion are 0.01  $m/s^2$  for both  $H_1$  and  $H_2$  components). This may explain why  $\Delta\kappa$  values  
172 are the same for the low and high intensity motions in the  $H_2$  component direction. Additionally,  
173 this observation also hints that the near-surface attenuation and site effects may be affected by the  
174 ground motion directionality as shown by Ji et al. (2020). Finally, soil nonlinearity is commonly  
175 observed at shallower layers (Régnier et al. 2013), and their effects on  $\kappa_r$  at borehole are smaller  
176 than at surface. Thus, the  $\kappa_r$  at borehole should be less affected by soil nonlinearity because it  
177 nonlinear soil behavior is less likely to be triggered at depth (e.g., the borehole  $V_s$  at FKSH14 is  
178 1210 m/s with borehole sensor depth of 147 m). In Figure 1, values of  $\kappa_r$  at borehole are similar  
179 for the high- and low-intensity motions. The changes in  $\kappa_r$  shown in Figure 1 exemplify the need

180 to further investigate the influence of the onset of soil nonlinearity on  $\kappa_r$  as well as the potential  
181 implications on  $\kappa_0$  values at a specific site.

182

183

### **Database description**

184 In this study, we use ground motions from the KiK-net database, which provides high quality  
185 strong ground motions recorded at more than 600 stations installed uniformly across Japan. Each  
186 station possesses a pair of sensors, one at the surface and another one at depth that is typically  
187 between 100 to 200 m deep. The sampling frequency of the observed acceleration series is either  
188 100 or 200 Hz. The P- and S-wave velocity profiles are measured by downhole PS logging and  
189 available at the KiK-net website (see Resources and Data). The earthquake information, including  
190 the seismic moment magnitude  $M_w$ , focal depth and epicenter location are provided by the  
191 broadband seismography network (F-net) catalog. The dataset used in this work was processed by  
192 Bahrampouri et al. (2020) with an automated protocol, which corrects the baseline and removes  
193 the background noise with a bandpass/high-pass acausal filter. The low-frequency filter corner  
194 frequency is determined based on a required value of the (signal+noise)/noise equal to 3,  
195 corresponding to a signal-to-noise ratio (SNR) of 2.0 (Boore and Bommer, 2005); this frequency  
196 ranges between predetermined minimum and maximum values of 0.05 and 0.5 Hz, respectively.  
197 The minimum high-frequency filter corner frequency is determined for a SNR of 1.0 (Douglas and  
198 Boore 2011). The minimum bandpass width is 60% of the range defined from zero to the Nyquist  
199 frequency. Further detailed descriptions on the ground motion processing are available in  
200 Bahrampouri et al. (2020).

201

202 We use surface and borehole records (only horizontal components) in this paper. The criteria  
203 applied to select records are as follows: (1) epicentral distance is less than 150 km, (2) the SNR  
204 ratio is larger than 3.0 at each frequency from 1.0 to 30 Hz, (3) focal depth is less than 35 km (Ji  
205 et al. 2020), and (4) the seismic wave path does not cross the Japanese volcanic belt (Nakano et al.  
206 2015). Thus, twenty stations with more than five nonlinear ground motions (the definition of  
207 nonlinear ground motions is described next in the Methods section) are used in this work (with 18  
208 stations having more than 10 nonlinear records and 8 stations having more than 15 nonlinear  
209 records, see Table 1). Table 1 provides local soil conditions and the number of ground motions at  
210 each selected site. The locations of selected stations are shown in Figure 2a, while the magnitude  
211 and distance distribution of selected ground motions is provided in Figure 2b.

212

213

## Method

### 214 Identification of the onset of nonlinearity

215 Identifying ground motions that trigger soil nonlinear behavior is key to evaluate  $\kappa$  estimates  
216 beyond the linear-elastic regime empirically. The shear-strain index ( $I_\gamma = PGV/V_s$ ), which is a  
217 proxy for the in-situ deformation, and PGA, which describes the peak amplitude of the ground  
218 motion, are commonly used to differentiate linear from nonlinear ground motions (e.g., Xu et al.  
219 2019, Cabas et al. 2017, Wang et al. 2019). Moreover, the correlation between PGA and  $I_\gamma$  has  
220 been shown to be an effective proxy to capture in-situ stress-strain relationships. This correlation  
221 has been characterized via the classic hyperbolic model, which fits empirical observations  
222 (Chandra et al. 2014, 2015, Guéguen et al. 2018). However, there is lack of consensus regarding  
223 the sufficiency and efficiency of existing proxies associated with the onset of nonlinear behavior.  
224 For example, Xu et al. (2019) assumed that records with  $I_\gamma$  less than 0.01% are linear ground

225 motions, while Cabas et al. (2017) adopted 0.1%. On the other hand, Ktenidou et al. (2013) chose  
226 a PGA of 0.1 m/s<sup>2</sup> as the threshold for linear ground motions. Régnier et al. (2013) conducted a  
227 statistical analysis on the KiK-net dataset to understand nonlinear site response at their stations.  
228 They characterized linear soil behavior as that associated with motions with a PGA at depth less  
229 than 0.1 m/s<sup>2</sup>.

230

231 We develop appropriate criteria to identify nonlinear ground motions based on PGA and  $I_\gamma$ . In this  
232 paper, the shear-strain index at the surface ( $I_{\gamma,0}$ ) is defined as follows:

$$233 \quad I_{\gamma,0} = PGV_{rotD50} / V_{s,0} \quad (1)$$

234 where  $V_{s,0}$  is the shear-wave velocity at the ground surface, and  $PGV_{rotD50}$  is the median PGV for  
235 all rotated surface ground motions following the approach of Boore (2010). The use of  $PGV_{rotD50}$   
236 rather than the PGV from recorded ground motion horizontal components can minimize  
237 directionality effects. The use of  $I_{\gamma,0}$  (Equation 1) as an indicator of the onset of soil nonlinearity  
238 has some limitations though. First, the selection of single  $V_s$  and PGV values to capture the depth-  
239 dependent deformation in the profile may underestimate or overestimate the level of nonlinearity  
240 experienced across the whole column. Thus,  $I_{\gamma,0}$ , as defined in Equation 1, serves simply as a proxy  
241 for a representative shear strain to take place in the sedimentary deposit of interest. Notably, there  
242 is no consensus regarding the most appropriate choice of  $V_s$  for  $I_\gamma$  estimates. For example,  $V_{s30}$  is  
243 a commonly used site proxy and hence often selected to compute  $I_\gamma$  (e.g., Kim et al. 2016, Guéguen  
244 et al. 2018). The equivalent  $V_s$  measured between two successive sensors with seismic  
245 interferometry by deconvolution has also been adopted for  $I_\gamma$  estimates (e.g., Chandra et al. 2015,  
246 2016, Wang et al. 2019). Second, values of  $I_{\gamma,0}$  are not directly comparable to shear strains  
247 measured in the laboratory, not only because  $I_\gamma$  is a proxy and not a measured value, but also

248 because the dissipation of seismic energy as captured in the laboratory may not fully represent the  
249 attenuation mechanisms taking place in the field (Cabas et al. 2017).

250

251 By applying the classic hyperbolic model to describe the correlation between  $PGA_{rotD50}$  and  $I_{\gamma,0}$ ,  
252 we find that there is no unique threshold to identify nonlinear ground motions across all study sites.  
253 Figure 3 provides examples of theoretical hyperbolic fitting curves at four stations (i.e., IBRH16,  
254 IBRH17, IBRH20 and IWTH21) with varying  $V_{s30}$  values (from 244 to 626 m/s) to demonstrate  
255 the limitations associated with using a single parameter to identify nonlinear ground motions at  
256 multiple sites. Scatter points represent  $PGA_{rotD50}$  and  $I_{\gamma,0}$  pairs from recorded ground motions at  
257 the sites of interest, while the lines correspond to the fitting curves from the hyperbolic model. It  
258 is observed that the same deformation at various sites would be triggered by different levels of  
259 ground shaking (e.g.,  $I_{\gamma,0}$  of 0.05% will be caused by a  $PGA_{rotD50}$  around 1 m/s<sup>2</sup> at a NEHRP D site,  
260 such as IBRH20 with  $V_{s30}$  of 244 m/s, and by a  $PGA_{rotD50}$  of 2 m/s<sup>2</sup> at a NEHRP C site, such as  
261 IBRH16 with  $V_{s30}$  of 626 m/s). On the other hand, if nonlinearity is assumed to be triggered when  
262 the  $PGA_{rotD50}$  is larger than a predetermined threshold, different levels of  $I_{\gamma,0}$  will be associated  
263 with the onset of soil nonlinearity. Hence, in this work, we propose a hybrid method (further  
264 described in the next section) based on both, the intensity of the excitation and in-situ deformation  
265 to classify ground motions.

266

### 267 **Linear, transitional, and nonlinear datasets**

268 Surface and borehole ground motions are considered separately herein. Régnier et al. (2013)  
269 considered that records with borehole PGA less than 0.1 m/s<sup>2</sup> cannot trigger nonlinear site response  
270 at the ground surface. They also observed that soil nonlinearity is mainly triggered at superficial

271 layers. In this study, there are only 3% records with borehole PGA larger than  $0.1 \text{ m/s}^2$ . Therefore  
272 the borehole records are assumed to remain in the linear-elastic regime (i.e., they do not trigger  
273 nonlinear behavior at depth). Surface records are separated into three sub-datasets, namely linear,  
274 transitional (i.e., soil's behavior is between the linear-elastic and nonlinear regimes), and nonlinear  
275 ground motions. First, we define a threshold based on  $I_{\gamma,0}$  to differentiate linear from transitional  
276 records, which is hereafter referred to as  $I_{\gamma,0,l}$ . Likewise, a transitional threshold,  $I_{\gamma,0,t}$ , is defined to  
277 separate transitional and nonlinear ground motions. The linear  $I_{\gamma,0,l}$  threshold is defined as the onset  
278 of soil nonlinearity by visual inspections of the corresponding  $\text{PGA}_{\text{rotD50}}$  versus  $I_{\gamma,0}$  curve, and  
279 corresponds to the point where  $\text{PGA}_{\text{rotD50}}$  values begin to increase at a higher rate with increasing  
280  $I_{\gamma,0}$ . The transitional  $I_{\gamma,0,t}$  threshold captures when the soil nonlinearity becomes more apparent,  
281 which corresponds to the point where the second change in slope of the  $\text{PGA}_{\text{rotD50}}$  versus  $I_{\gamma,0}$  curve  
282 takes place. Figure 4 provides an example of the selection of  $I_{\gamma,0,t}$  and  $I_{\gamma,0,l}$  at station MYGH10. The  
283 threshold separating the linear and transitional ground motions is  $I_{\gamma,0,l} = 0.001\%$ , while the  
284 threshold separating transitional and nonlinear ground motions is  $I_{\gamma,0,t} = 0.007\%$ .

285  
286 A maximum  $\text{PGA}_{\text{rotD50}}$  of  $0.25 \text{ m/s}^2$ , which is the value adopted by Régnier et al. (2016) to define  
287 low-amplitude motions, is chosen as an additional constraint to avoid linear ground motions being  
288 erroneously included into the nonlinear dataset. Thus, linear, transitional, and nonlinear datasets  
289 are defined as follows:

- 290 ○ Linear ground motions: records with  $I_{\gamma,0}$  less than the  $I_{\gamma,0,l}$  threshold.
- 291 ○ Nonlinear ground motions: records with (a)  $I_{\gamma,0}$  larger than the  $I_{\gamma,0,t}$  threshold and (b)  
292  $\text{PGA}_{\text{rotD50}}$  larger than  $0.25 \text{ m/s}^2$ .
- 293 ○ Transitional ground motions: records not classified as either linear or nonlinear.

294

295 The validity of the proposed linear, transitional, and nonlinear datasets is tested by examining the  
296 behavior of the shear modulus,  $G$  against  $I_{\gamma,0}$  at the study sites. The reduction of  $G$  for empirical  
297 ground motions is estimated as follows (after Guéguen et al., 2019):

$$298 \quad \frac{G}{G_{\max}} = \frac{PGA_{rotD50}}{PGV_{rotD50}/V_{s,0}} \left/ \left( \frac{PGA_{rotD50}}{PGV_{rotD50}/V_{s,0}} \right)_{\max} \right. \quad (2)$$

299 The term  $\left( \frac{PGA_{rotD50}}{PGV_{rotD50}/V_{s,0}} \right)_{\max}$  is computed from the corresponding average ratio of records with

300  $I_{\gamma,0}$  less than 0.001%, which is the predetermined threshold of  $I_{\gamma,0,1}$  for the linear-elastic deformation  
301 limit in this work. Figure 5 shows the  $G/G_{\max}$  versus  $I_{\gamma,0}$  curves at all study sites. Even though  
302 Figure 5 does not directly correspond to laboratory-based curves, it serves as a first order  
303 verification of the distinct behavior corresponding to the linear, transitional, and nonlinear ground  
304 motions identified with the categorization scheme proposed herein. One challenge when  
305 interpreting these data is the characterization of the soil volume being sampled when using  $I_{\gamma}$ ,  
306 which is related to the frequency band that PGV is acting on. Identified linear ground motions  
307 mainly have  $G/G_{\max}$  values around 1 ( $G/G_{\max}$  values higher than 1 result from using mean  $G$  values  
308 as a proxy for  $G_{\max}$ ), while the ratios corresponding to the nonlinear dataset are generally less than  
309 1 due to the onset of soil nonlinearity. Notably, values of  $G/G_{\max}$  associated with the transitional  
310 dataset are between the linear and nonlinear datasets. It is not clear whether the site response  
311 associated with records identified as transitional could be equivalent to a linear-elastic or a  
312 nonlinear response, because associated  $G/G_{\max}$  values vary within a single station and across  
313 stations. Hence, the characterization as transitional is deemed appropriate herein.

314

315  **$\kappa_{r\_AS}$  estimates**

316 We use the acceleration spectrum approach (Anderson and Hough, 1984) to estimate  $\kappa_{r\_AS}$ . To  
317 minimize the variability introduced by the selection of the S-wave window, the entire time series  
318 is used. Because compatibility with engineering analysis such as geotechnical site response  
319 analysis and ground motion models is also desired, and such applications use complete time series,  
320 calculating  $\kappa_{r\_AS}$  using the entire time series is convenient. Moreover, the differences of  $\kappa_{r\_AS}$   
321 values measured from S-wave window and the entire time series are not significant in most cases  
322 (Ji et al. 2020). In this study, a subset of randomly selected ground motions is used to further assess  
323 potential discrepancies between using the S-wave window relative to the entire time series, and no  
324 significant differences are observed. Hence, the entire time histories are used.

325

326 The variability in estimates of  $\kappa_{r\_AS}$  is a function of the selection of the frequency band (Edwards  
327 et al. 2015, Perron et al. 2017) among other factors (Ji et al. 2020, Ktenidou et al. 2013). Moreover,  
328 soil nonlinearity affects low and high frequencies differently. The onset of nonlinear soil behavior  
329 can influence high frequencies first (Bonilla et al. 2011, Bonilla and Ben-Zion, 2020) because  
330 larger shear strains are induced in softer, thinner layers located at shallower depths (i.e., in a profile  
331 with increasing stiffness with depth). Hence, we compute  $\kappa_{r\_AS}$  based on a pre-determined fixed  
332 frequency window ( $[f_1, f_2]$ ). The pre-determined  $f_1$  corresponds to the maximum value between  $1.4$   
333  $f_c$  (where  $f_c$  is the earthquake source corner frequency of each record) and  $1.4 f_0$  (where  $f_0$  is the  
334 site's predominant frequency). Indeed, if  $f_1$  is lower than  $f_0$ , the value of  $\kappa_{r\_AS}$  will be biased by the  
335 site amplification in the high-frequency range (Parolai and Bindi 2004). On the other hand, the  $f_c$   
336 requirement is added to reduce the effects of the earthquake source. The value of  $f_2$  is set to be 25



337 Hz due to consideration of KiK-net instrument's response (Aoi et al., 2004, Fujiwara et al. 2004,  
338 Oth et al. 2011, Laurendeau et al. 2013). These limits ensure a broad frequency bandwidth for  $\kappa$   
339 calculations of at least 10 Hz per record, which reduces potential bias from local amplification  
340 effects (Parolai and Bindi, 2004; Ktenidou et al. 2016). The arithmetic average of the resulting  
341  $\kappa_{r\_AS}$  estimated from two orthogonal horizontal components is used because it is not affected by  
342 the record azimuth and its implementation can reduce the variability in  $\kappa_{r\_AS}$  caused by ground  
343 motion directionality (Ji et al. 2020). However, a prescribed, fixed-frequency band does not  
344 guarantee the most appropriate linear regression for the high-frequency spectral decay in all cases.  
345 Thus, we further investigate the performance of the fixed-frequency window and the effects of the  
346 frequency band selection for weak and strong ground motion records by comparing individual  
347  $\kappa_{r\_AS}$  values estimated from a pre-determined fixed frequency window with their counterparts,  
348  $\kappa_{r\_auto}$ , resulting from an automated algorithm which does account for the most appropriate linear  
349 regression.

350

351 The automated procedure used in this paper follows a similar protocol as those presented in  
352 Sonnemann, and Halldorsson (2017) and Pilz et al. (2019), which focus on finding an appropriate  
353 frequency band ( $[f_l, f_2]$ ) to describe the linear decay in the high frequency range over a relatively  
354 broad frequency window. As part of the automated protocol, the minimum  $f_l$  is selected as the  
355 maximum value between  $1.4f_0$ , and  $1.4f_c$ . To ensure a minimum frequency bandwidth of 10 Hz,  
356 the maximum value of  $f_l$  is 15 Hz and the minimum  $f_2$  corresponds to  $(f_l + 10)$  Hz. With 0.5 Hz  
357 increments in  $f_l$  and  $f_2$ ,  $f_l$  is varied from the maximum value between  $1.4f_0$  and  $1.4f_c$  to 15 Hz, while  
358  $f_2$  changes from  $(f_l + 10)$  Hz to 25 Hz. Going through all the possible combinations of  $f_l$  and  $f_2$ , the  
359 frequency range with the minimum root mean square error over the frequency bandwidth is set as

360 the optimal frequency band. The errors are computed with the following equation after Pilz et al.  
361 (2019):

$$362 \quad P = \frac{RMS}{\sqrt{\Delta f}} \quad (3)$$

363 Where  $\Delta f$  is the frequency bandwidth, and RMS is the root mean square error between the fitting  
364 line and smoothed FAS. The FAS is smoothed with the Konno-Ohmachi filter with a coefficient  
365 of 40 (Konno and Ohmachi, 1998). It should be noted that this automated procedure returns  $\kappa_{r,auto}$   
366 values associated with an appropriate regression for a broad frequency band. However, the changes  
367 of the FAS shape in high frequencies caused by site effects or soil nonlinearity (e.g., bumps or  
368 multiple linear trends) may not be properly accounted for by the automated algorithm.

369  
370 Figure 6 compares  $\kappa_{r\_AS}$  and  $\kappa_{r, auto}$  for all selected ground motions at FKSH14, where overall  
371 similar  $\kappa_{r\_AS}$  and  $\kappa_{r, auto}$  estimates are observed and discrepancies are more significant at the ground  
372 surface than at depth. The remaining stations also show an acceptable agreement between the two  
373 methods at the surface and at depth. However, there are few records that show significant  
374 differences between  $\kappa_{r\_AS}$  and  $\kappa_{r, auto}$  (e.g., one surface record has  $\kappa_{r\_AS}$  of about 0.025 s, while  $\kappa_{r, auto}$   
375  $\kappa_{r, auto}$  is almost 0.05 s). This reflects the variability of  $\kappa_r$  as a function of the frequency band  
376 selected. For example, there are 13% of records at AICH17 showing clear variations with the  
377 frequency band selection based on the coefficient of variation (COV) obtained for all frequency  
378 windows evaluated by the automatic procedure (i.e., COV larger than 0.15). Differences between  
379  $\kappa_{r\_AS}$  and  $\kappa_{r, auto}$  are mainly caused by some empirical FAS shapes, for example, when multiple  
380 linear decaying trends are present in the high-frequency range. The latter cannot be captured by  
381 the single linear decay assumption within the  $\kappa$ -model. More research is needed to study how more

382 complex wave propagation effects in the high frequency range can be captured. Testing the  
383 appropriateness of the  $\kappa$ -model as introduced by Anderson and Hough (1984) for these cases is  
384 outside the scope of this study, but it constitutes an area of relevant future research.

385

386 Negative  $\kappa_{r\_AS}$  values are excluded from this work. Overall, there are 14 of 20 stations with less  
387 than 20% negative  $\kappa_{r\_AS}$  values (i.e., arithmetic means of two horizontal components), and 1 of 20  
388 stations with more than 50% negative  $\kappa_{r\_AS}$  estimates. To further understand the observed negative  
389  $\kappa_{r\_AS}$  values, the corresponding FAS are reinspected. These FAS generally show bumps or multiple  
390 linear decays in high frequencies. The pre-determined frequency band used in this study is then  
391 not able to capture the linear decay appropriately and leads to negative  $\kappa_{r\_AS}$  values. Moreover,  
392 amplifications at higher frequencies may also affect estimates of  $\kappa_{r\_AS}$  and lead to negative values.  
393 The original  $\kappa_r$  model (i.e., the linear decay of FAS in log-linear scale for high frequency ranges  
394 per record proposed by Anderson and Hough, 1984), requires the site response at the site of interest  
395 to be almost flat in the high frequency range. Complex in-situ site conditions that lead to high  
396 frequency amplification (e.g., heterogeneities in the near-surface, and/or shallow impedance  
397 contrasts) can challenge this simple linear decay model. Our observations suggest the need to  
398 further explore the limitations and simplified assumptions of the Anderson and Hough (1984)  $\kappa_r$   
399 model for it to be applicable or extended to more complex environments and stronger ground  
400 shaking. Accounting for the discrepancies between actual field conditions and assumptions  
401 suggested by the Anderson and Hough (1984)  $\kappa$  model could reduce the large variability observed  
402 in  $\kappa_{r\_AS}$  estimates. Further research should focus on evaluating the limitations of the Anderson and  
403 Hough (1984) model and its potential modification to capture more complex wave propagation  
404 patterns in heterogeneous media, especially near the surface. In this work, such an investigation is

405 not included, but future efforts of the authors envision the assessment of negative  $\kappa_{r\_AS}$  estimates  
406 observed in this work as a first step to improve the existing  $\kappa$  model.

407

#### 408 **$\kappa_0$ -model**

409  $\kappa_{r\_AS}$  is generally modeled with contributions from a site-specific component ( $\kappa_0$ ), a path  
410 component ( $\kappa_R$ ), and a source component ( $\kappa_s$ ). The source component,  $\kappa_s$ , is often assumed to be  
411 negligible and its contribution is reduced by using a dataset with sufficient records (Van Houtte et  
412 al. 2011, Ktenidou et al. 2014). A linear distance-dependency model is commonly applied to  
413 capture the path component  $\kappa_R$ , which represents source-to-site effects or regional attenuation  
414 (Hough et al. 1988, Anderson, 1991, Ktenidou et al. 2013, Boore and Campbell, 2017). Thus, the  
415 most commonly accepted model is described below:

$$416 \quad \kappa_{r\_AS} = \kappa_0 + \kappa_R \times R_e \quad (4)$$

417 where  $\kappa_0$  and  $\kappa_{r\_AS}$  are in units of time (s),  $\kappa_R$  is in units of second per kilometer (s/km) and  $R_e$   
418 refers to epicentral distance in km. This model is valid when a unique source-to-site path is  
419 assumed for each record along with a homogeneous and frequency-independent seismic quality  
420 factor  $Q$  (Knopoff 1964). In this paper, the assumption of a unique source-to-site path is supported  
421 by using ground motions with  $R_e$  less than 150 km (e.g., Palmer and Atkinson 2020, Cabas et al.  
422 2017, Ktenidou et al. 2013). In addition, ground motions whose travel path crosses Japan's  
423 volcanic belt are not included in our database to minimize the likelihood of seismic waves  
424 propagating through regions with varying  $Q$  values (Pei et al. 2009, Nakano et al. 2015).

425

426 The model described by Equation (4) is straightforward to apply when only surface linear ground  
427 motion datasets are used. However, the incorporation of nonlinear and borehole ground motions

428 adds complexity to the estimation of regional attenuation as captured by  $\kappa_R$ . In this paper, we  
 429 assume that soil nonlinearity is triggered near the surface, which is consistent with previous studies  
 430 showing that nonlinear behavior occurs mostly in the superficial soil layers (i.e., Régnier et al.,  
 431 2013; Bonilla et al., 2019; Qin et al., 2020). Thus, nonlinear soil behavior is treated as a site  
 432 contribution rather than a path contribution, and we assume the regional attenuation to be identical  
 433 for linear and nonlinear ground motions recorded at the ground surface and at depth.

434  
 435 Analogous to the formulation suggested by Douglas et al. (2010) for soil and rock sites, we propose  
 436 a model based on Equation (4), which includes linear and nonlinear surface and borehole records:

$$437 \quad \kappa_{r\_AS} = N_1 \kappa_{0\_depth} + N_2 \kappa_{0\_lin\_sur} + N_3 \kappa_{0\_nl\_sur} + N_4 \kappa_{0\_tran\_sur} + \kappa_R \times R_e \quad (5)$$

438 where  $\kappa_{0\_depth}$  is the site-specific  $\kappa_0$  at depth (i.e., depth of borehole sensor), and  $\kappa_{0\_lin\_sur}$ ,  $\kappa_{0\_tran\_sur}$   
 439 and  $\kappa_{0\_nl\_sur}$  are the site-specific linear, transitional and nonlinear  $\kappa_0$  at the surface. The coefficients  
 440  $N_1$ ,  $N_2$ ,  $N_3$ , and  $N_4$  are defined as follows:

$$441 \quad N_1 = \begin{cases} 1 & \text{for dataset at depth} \\ 0 & \text{otherwise} \end{cases}$$

$$442 \quad N_2 = \begin{cases} 1 & \text{for linear dataset at surface} \\ 0 & \text{otherwise} \end{cases}$$

$$443 \quad N_3 = \begin{cases} 1 & \text{for nonlinear dataset at surface} \\ 0 & \text{otherwise} \end{cases}$$

$$444 \quad N_4 = \begin{cases} 1 & \text{for transitional dataset at surface} \\ 0 & \text{otherwise} \end{cases}$$

445 The parameter  $N_4$  in Equation (5) only takes a value of 1 when ground motions classified as  
 446 transitional are considered independently and not as part of the linear or nonlinear datasets. That  
 447 means that when transitional ground motions are excluded from analysis (i.e., AP1, see Table 2)  
 448 or included into either the linear (i.e., AP2, see Table 2) or nonlinear (i.e., AP3, see Table 2)  
 449 datasets, the coefficient  $N_4$  will be equal to zero.

450

451

## Results and Discussion

### 452 Effects of soil nonlinearity on empirical $\kappa_{r\_AS}$

453 First, we study the influence of soil nonlinearity on  $\kappa_{r\_AS}$  estimates per record at each site. It should

454 be noted that soil nonlinearity is commonly triggered at shallower soil layers (Régner et al. 2013),

455 so we only focus on surface records in this section. Figure 7 depicts calculated  $\kappa_{r\_AS}$  values at the

456 surface against the corresponding  $I_{\gamma,0}$  values at FKSH14 ( $V_{s30} = 237$  m/s) and MYGH10 ( $V_{s30} =$

457 348 m/s). As described in Equation (4),  $\kappa_{r\_AS}$  is affected by both local site conditions and path

458 effects in the context of a linear-elastic deformation analysis. Hence, the colorbar in Figure 7

459 represents varying epicentral distances, and the sizes of markers represent the corresponding

460  $PGA_{rotD50}$ . An overall increasing trend of  $\kappa_{r\_AS}$  with increasing intensity of ground shaking (either

461 evidenced by increased PGA or  $I_{\gamma,0}$  values) is observed at FKSH14 for events that share similar

462 epicentral distances. A slightly decreasing trend is observed for short-distance records with  $R_e$  less

463 than about 50 km and high  $PGA_{rotD50}$ . However,  $\kappa_{r\_AS}$  values corresponding to those shorter

464 distance and higher  $PGA_{rotD50}$  events (i.e., the largest circles in Figure 7a) are larger than their

465 counterparts for low-intensity motions (i.e., the smallest circles in Figure 7a) regardless of the  $R_e$ .

466 To the best knowledge of the authors, this observation has not been reported before and could be

467 associated with the depth of influence of  $\kappa_r$ . Variations in  $\kappa$  due to strong nonlinear effects may be

468 a function of a more significant contribution of the site to the overall attenuation, which may not

469 be necessarily the case for smaller amplitude events. There might be several mechanisms of

470 attenuation combined, and their contributions as captured by  $\kappa$  need to be further investigated.

471 Similar trends are observed at other seven sites with  $V_{s30}$  less than 400 m/s, which include AICH17,

472 CHBH13, FKSH11, IBRH20, IWTH26, MYGH07, and TCGH16, and at KMMH12 with  $V_{s30}$   
473 greater than 400 m/s.

474

475 The increasing  $\kappa_{r\_AS}$  trend with increasing  $PGA_{rotD50}$  and  $I_{\gamma,0}$  is not as significant at MYGH10  
476 (Figure 7b), which has relatively stiffer site conditions than FKSH14. Either no correlation or a  
477 slightly decreasing trend is found at other stiff sites with  $V_{s30}$  greater than 400 m/s (i.e., FKSH21,  
478 NIGH12, NGNH29, NIGH07, KMMH01, and IBRH16), and at four softer sites with  $V_{s30}$  between  
479 300 and 400 m/s (i.e., IWTH21, FKSH18, FKSH19, and IBRH17). We note that the number of  
480 available nonlinear records for the  $R_e$  ranges at the sites where the decreasing trend is observed is  
481 rather limited. Additional nonlinear records at those sites are necessary (i.e., stronger intensity  
482 ground motions) to further evaluate the contributing factors to a potential decreasing trend in  $\kappa_{r\_AS}$   
483 values. However, in general, we observe that positive correlations between  $\kappa_{r\_AS}$  and the intensity  
484 of ground shaking are more significant at softer sites (e.g., TCGH16 with  $V_{s30}$  of 213 m/s) than at  
485 stiffer sites (e.g., KMMH12 with  $V_{s30}$  of 408 m/s). These data support that the onset of soil  
486 nonlinearity can affect  $\kappa_{r\_AS}$  estimates, but such influence is station-dependent. The level of soil  
487 nonlinearity can be unique at each site (for a similar intensity of ground shaking) because of the  
488 characteristics of shallow geologic structures (e.g., differences in velocity gradients and seismic  
489 impedance contrasts) and the location of low shear-wave velocity layers. Thus, subsurface  
490 conditions can play a key role on the effects of nonlinearity on  $\kappa_{r\_AS}$ . We observe the same patterns  
491 shown in Figure 7 when using our results from the automated procedure to compute  $\kappa_{r\_auto}$ .

492

493 **Effects of soil nonlinearity on the empirical  $\kappa_0$ -model**

494 Linear, transitional, and nonlinear ground motion datasets are used in this section to evaluate the  
495  $\kappa_0$ -model beyond the linear-elastic regime. We explore four approaches (i.e., AP1 to AP4) to  
496 incorporate records within the transitional dataset into the  $\kappa_0$ -model presented in Equation (5).  
497 Table 2 summarizes how the identified linear, transitional, and nonlinear datasets are used to  
498 estimate  $\kappa_{0\_lin\_sur}$  and  $\kappa_{0\_nl\_sur}$ .

499  
500 Figures 8 and 9 present the resulting  $\kappa_0$  models from each approach at FKSH14 and MYGH10,  
501 respectively. Figure 8 shows that  $\kappa_{r\_AS}$  and  $\kappa_0$  values corresponding to the nonlinear ground  
502 motions (regardless of the selected approach to construct the nonlinear dataset) are larger than their  
503 linear counterparts at FKSH14. However, results at the stiffer station presented in Figure 9 show  
504 little disagreement between  $\kappa_{r\_AS}$  and  $\kappa_0$  values corresponding to the linear and nonlinear motions  
505 (regardless of the approach to construct each dataset).

506  
507 Variations in  $\kappa_{0\_lin\_sur}$  estimates are observed as a function of the approach considered to construct  
508 the linear datasets (see specific values in Table 3 for FKSH14 and MYGH10, the results for other  
509 selected stations are available in the electronic supplement). Similarly, variations in  $\kappa_{0\_nl\_sur}$  values  
510 are also found across the different approaches to define the nonlinear datasets. At FKSH14 (Figure  
511 8),  $\kappa_{0\_lin\_sur}$  estimates are more variable as a function of the dataset definitions (with a maximum  
512 difference of 15.83% across approaches AP1 to AP4), compared to  $\kappa_{0\_nl\_sur}$  values (with a  
513 maximum difference of 5.10%). In addition, Figure 8 (d) shows that data points corresponding to  
514 the transitional dataset are more compatible with their counterparts within the nonlinear dataset,  
515 which may indicate that at FKSH14, the level of nonlinearity induced by the transitional dataset is



516 closer to that induced by the ground motions in the nonlinear dataset. Other study sites such as  
517 AICH17 ( $V_{s30} = 314$  m/s) and IWTH21 ( $V_{s30} = 521$  m/s) also show that  $\kappa_{0\_lin\_sur}$  estimates are more  
518 sensitive to dataset selections. In contrast, variations of  $\kappa_{0\_lin\_sur}$  and  $\kappa_{0\_nl\_sur}$  across datasets at  
519 MYGH10 (Figure 9) are small, with maximum differences of only 1.56% and 2.53%, respectively.  
520 Large differences in  $\kappa_{0\_nl\_sur}$  estimates across datasets are observed at eight sites, but the limited  
521 number of nonlinear records at some of those sites may be the main contributing factor (e.g., there  
522 are only six nonlinear records at IWTH21, which results in a maximum difference of 47.05% for  
523  $\kappa_{0\_lin\_sur}$  and 11.17% for  $\kappa_{0\_nl\_sur}$ ). Adding transitional records to either the linear or the nonlinear  
524 dataset at such sites can bias the regression model. In general, differences in the  $\kappa_0$ -model as a  
525 function of the selected dataset are observed in 45% of our study sites (with differences in  $\kappa_{0\_lin\_sur}$   
526 or  $\kappa_{0\_nl\_sur}$  values greater than 10%). This is a relevant observation because it demonstrates the  
527 importance of selecting appropriate ground motions even for typical  $\kappa_0$  estimations (i.e., in the  
528 linear-elastic regime) at a given site.

529  
530 Our findings suggest that the development of a  $\kappa_0$ -model beyond the linear-elastic regime requires  
531 an evaluation of the definition of what constitutes linear and nonlinear ground motion datasets.  
532 The identification of transitional ground motion datasets in this study allows us to assess which  
533 records provide estimates of  $\kappa_{r\_AS}$  that are closer to either the linear or the nonlinear behavior at  
534 different sites. Differences in behavior triggered by the records within the transitional database  
535 may be caused by unique local site conditions (i.e., the level of soil nonlinearity developed at each  
536 site) or by limitations of the simplified definition used herein to classify transitional records (i.e.,  
537 as a function of PGA and  $I_T$ ). Identifying appropriate linear and nonlinear datasets for  $\kappa_{r\_AS}$   
538 estimations requires further research to provide consistent models of near-surface attenuation that

539 can more effectively be implemented from small to large shear strains. However, the site-specific  
540 response at a site of interest may impose challenges in determining appropriate dataset  
541 classifications based on a simple, generalized criterion.

542

543 Figure 10 provides ratios of  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  at the 20 study sites against the corresponding time-  
544 average  $V_s$  value in the top 5 m ( $V_{s5}$ ), 10 m ( $V_{s10}$ ), and 30 m ( $V_{s30}$ ). The ratios are computed based  
545 on the AP3 and AP4 approaches to construct linear and nonlinear datasets (Table 2). Larger ratios  
546 are observed at softer sites regardless of the dataset chosen (i.e., AP3 and AP4) for the  $\kappa_0$ -model.  
547 Differences between  $\kappa_0$  values in the linear and nonlinear regimes seem to be reconciled at sites  
548 with higher  $V_{s5}$  ( $> 300$  m/s),  $V_{s10}$  ( $> 300$  m/s) and  $V_{s30}$  ( $> 400$  m/s) values, where the ratios fluctuate  
549 more closely around unity particularly when using AP3. The trend of increasing ratios of  
550  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  with softer site conditions is better captured by  $V_{s5}$  and  $V_{s10}$  than by  $V_{s30}$ , because  
551 soil nonlinearity is more likely triggered at shallower and softer layers (Régner et al. 2013). Hence,  
552 lower  $V_s$  layers may dominate soil nonlinearity effects on  $\kappa_0$ . Thus, site proxies that can  
553 characterize such near-surface layers may be more informative when evaluating nonlinear soil  
554 effects on  $\kappa_0$ .

555

556 When grouping transitional and nonlinear ground motions (i.e., AP3), most stations result in ratios  
557 of  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  larger than one, which can be interpreted as the signature of soil nonlinearity  
558 on the near-surface attenuation estimates (i.e., near-surface attenuation increases with increasing  
559 deformations as soil nonlinearity is triggered). These findings are consistent with the behavior of  
560 material damping ratio observed in dynamic laboratory testing of soils (i.e., increased damping  
561 ratio with increasing shear strain; Darendeli 2001; Menq 2003; Ishibashi and Zhang 1993). When

562 treating linear, transitional, and nonlinear datasets independently (i.e., AP4), there are 12 sites with  
563 ratios larger than one. The instances where ratios of  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  are lower than one may result  
564 from the limited nonlinear records available at those sites coupled with the uncertainties associated  
565 with  $\kappa_{0\_lin\_sur}$  (e.g., Ji et al., 2020).

566

567 Overall, the variations observed in the  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  ratio support our hypothesis that soil  
568 nonlinearity plays a role on the estimates of near-surface attenuation from recorded ground  
569 motions. This effect is station-dependent, and further research is needed to identify the most  
570 appropriate parameter or vector of parameters capable of capturing the influence of nonlinear soil  
571 behavior on near-surface attenuation. Moreover, the relatively weaker correlation between  $V_{s30}$   
572 and the  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  ratio evidences the challenges in connecting site conditions and soil  
573 nonlinearity via a single site parameter. Multiple parameters that can describe attenuation and  
574 impedance effects from the shallow and deep geologic structures should be investigated. The  
575  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  ratio corresponding to IWTH21 ( $V_{s30}=521$  m/s) is not shown in Figure 10 because  
576 it is very large (i.e., approximately 1.8). This observation may result from uncertainties associated  
577 with  $\kappa_{r\_AS}$  values propagating to estimates of  $\kappa_0$  when the fixed frequency band approach is applied  
578 for all records without consideration of the optimal linear decay trend. In fact, the corresponding  
579  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  ratio when implementing the automated procedure is approximately 0.90 for this  
580 station. Finally, Figure 10 shows less scatter in  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  ratios when using datasets defined  
581 by AP3. In addition, using AP3 results in ratios either larger than one or approaching one for most  
582 stations (i.e., only FKSH19 and KMMH01 results in a ratio lower than unity), which is consistent  
583 with our conceptual basis for increased attenuation with the onset of nonlinear soil behavior.

584 Therefore, we adopt the AP3 approach (which includes transitional records into nonlinear dataset)  
585 to evaluate predictions of near-surface attenuation in the next section of this paper.

586

### 587 **Effects of soil nonlinearity on predicted near-surface attenuation**

588 Site-specific  $\kappa_{0\_lin\_sur}$  or  $\kappa_{0\_nl\_sur}$  values from Equation (5) allow for the comparison of empirical  
589 estimates of near-surface attenuation, but these two parameters represent the average attenuation  
590 of all records in linear and nonlinear regimes. Thus, in this section, we introduce the predicted  
591 near-surface attenuation at zero-distance ( $\kappa_{0\_pred}$ ), which is expected to capture the attenuation  
592 contributed by the superficial soil layers per event by removing the path contributions from  $\kappa_{r\_sur}$ .  
593  $\kappa_{0\_pred}$  is modeled as:

$$594 \quad \kappa_{0\_pred} = \kappa_{r\_AS\_sur} - R_e \bullet \kappa_R \quad (6)$$

595 where  $\kappa_{r\_AS\_sur}$  refers to the individual  $\kappa_{r\_AS}$  value for a surface ground motion, and the path-  
596 component,  $\kappa_R$ , corresponds to the values derived with Equation (5) at each site of interest. We  
597 assume that by removing the effect of the path-component  $\kappa_R$  from  $\kappa_{r\_AS\_sur}$  values per record, the  
598 remaining  $\kappa_{0\_pred}$  becomes an approximation to the attenuation contributed by the shallower  
599 sedimentary deposits per event. Thus, we can explore how the near-surface attenuation changes  
600 with the various input ground motion amplitudes at the site of interest.

601

602 Figure 11 provides comparisons between  $\kappa_{0\_pred}$ , ground shaking intensity, and deformation as  
603 captured by  $PGA_{rotD50}$  and  $I_{7,0}$  at FKSH14 and MYGH10. Both colors and sizes of markers  
604 represent the  $PGA_{rotD50}$  values per record. The red dashed-lines result from a local regression model  
605 characterizing the  $\kappa_{0\_pred}$  versus  $I_{7,0}$  data. Triangles and circles represent the linear and nonlinear

606 ground motions (identified with AP3), respectively. Values of  $\kappa_{0\_pred}$  first increase and then  
607 decrease with increasing  $PGA_{rotD50}$  and  $I_{\gamma,0}$  at FKSH14. This behavior is also observed at other 7  
608 sites (i.e., AICH17, CHBH13, FKSH11, IWTH26, KMMH12, MYGH07, TCGH16). Even with  
609 the decreasing trend for large  $I_{\gamma,0}$ ,  $\kappa_{0\_pred}$  is still generally higher than its counterpart in the linear  
610 regime (i.e., the means of linear and nonlinear  $\kappa_{0\_pred}$  are 0.050 sec and 0.0605 sec, respectively).  
611 Overall,  $\kappa_{0\_pred}$  values at FKSH14 corresponding to larger deformations and higher  $PGA_{rotD50}$  are  
612 larger than those corresponding to weaker ground motions. In contrast, only a weak correlation to  
613 the intensity of ground shaking and deformation in situ is observed at MYGH10. These results are  
614 consistent with our estimations of  $\kappa_r$  shown in Figure 7. Soil nonlinear behavior can influence  
615 near-surface attenuation as captured by  $\kappa_r$  and  $\kappa_0$ , and local site conditions may play a key role in  
616 this process. The remaining approaches explored in this study (i.e., AP1, AP2, and AP4) provide  
617 similar results as those shown in Figure 11.

618  
619 Figure 12 compares the probability distribution of  $\kappa_{0\_pred}$  values from the linear and nonlinear  
620 datasets (AP3 case) at FKSH14 and MYGH10. The resulting  $\kappa_{0\_pred}$  values are fitted with a  
621 Gaussian distribution and the corresponding probability density functions (PDFs) are represented  
622 by red lines. A shift to the right (i.e., toward larger  $\kappa_{0\_pred}$  values) of the theoretical PDF is observed  
623 at FKSH14 as ground motions from the linear and nonlinear datasets are considered. The mean  
624  $\kappa_{0\_pred}$  estimates change from 0.05 s for the linear dataset to 0.0605 s for the nonlinear dataset at  
625 FKSH14 (i.e., a difference of 21%). In contrast, the variation of mean  $\kappa_{0\_pred}$  between linear and  
626 nonlinear datasets at MYGH10 is 4%. Most of our study sites have either a significant increase in  
627 their mean  $\kappa_{0\_pred}$  when using the nonlinear dataset (i.e., an increase of more than 20%) or only a  
628 slight increase. There are only 4 stations that show a decrease in their mean  $\kappa_{0\_pred}$  values with

629 respect to the linear dataset when using the nonlinear one (i.e., FKSH19, KMMH01, NIGH07, and  
630 NIGH12). Statistical hypothesis tests (i.e., t-test) are conducted to analyze whether there is a  
631 statistically significant difference between the means of linear and nonlinear  $\kappa_{0\_pred}$  distributions.  
632 Considering a critical value of 5%, p-values at each station are shown in Table 4. Nine out of 20  
633 stations display statistically significant differences between their mean  $\kappa_{0\_pred}$  corresponding to the  
634 linear and nonlinear datasets. Table 4, Figures 11 and 12 show that soil nonlinear behavior can  
635 affect  $\kappa_{0\_pred}$  at the sites selected in this study, although this influence is station-dependent. At the  
636 stations that display apparent effects of nonlinearity on  $\kappa$ , an increasing trend in predicted near-  
637 surface attenuation with increasing ground shaking intensity and/or increasing deformation is  
638 observed.

## 639 **Conclusions**

640 In this work, we investigated the influence of soil nonlinear behavior on  $\kappa_{r\_AS}$  values per record  
641 and site-specific  $\kappa_0$  estimates at 20 stations selected from the KiK-net database. To avoid potential  
642 bias on our results due to the calculation process, we also examined the effects of the frequency  
643 band selection on  $\kappa_{r\_AS}$  estimates, and the differences between using the S-wave window or the  
644 entire time series FAS. We compared results from a predetermined fixed-frequency window  
645 approach with an automated procedure that considers multiple frequency windows. The latter is  
646 capable of finding the optimal frequency band per record for all records at each site. The selection  
647 of a common, fixed and broader frequency band for  $\kappa_{r\_AS}$  estimations reduced the scatter and bias  
648 in the data, while providing reasonable estimations of  $\kappa_{r\_AS}$ . On the other hand, values of  $\kappa_{r\_AS}$   
649 computed from the S-wave window FAS were reasonably similar to their counterparts based on  
650 the entire time series FAS. Hence, the analyses presented in this paper were conducted with  $\kappa_r$

651 values estimated by the fixed-frequency band approach and the FAS corresponding to the entire  
652 time series.

653

654 A consistent identification of ground motions that trigger nonlinear behavior in sedimentary  
655 deposits is also necessary to quantify near-surface attenuation beyond the linear-elastic regime.

656 Based on the examination of an in-situ stress-strain proxy, namely the correlation between

657  $PGA_{rotD50}$  and  $I_{\gamma,0}$ , we found that the variation of shear strains with ground shaking intensity at the

658 onset of nonlinear soil behavior is site-specific. A unique threshold for a single parameter, whether

659 it is  $PGA_{rotD50}$  or  $I_{\gamma,0}$ , was not able to capture the onset of soil nonlinearity at our study sites in a

660 consistent manner across all sites. Hence, we proposed a hybrid method to classify linear and

661 nonlinear ground motions considering both,  $PGA_{rotD50}$  and  $I_{\gamma,0}$ , which resulted in linear, transitional,

662 and nonlinear datasets at each site.

663

664 Increasing  $\kappa_{r\_AS}$  values with increasing  $PGA_{rotD50}$  or  $I_{\gamma,0}$  for ground motions with similar epicentral

665 distances were observed at about half of our study sites. This trend was more consistently observed

666 at softer sites. Additionally, we found that  $\kappa_0$ -models could be biased by the definition of linear

667 and nonlinear ground motion datasets. Hence, we studied the effects of ground motion

668 categorization and proposed a hybrid classification scheme for linear and nonlinear records. We

669 defined transitional ground motions as those associated with soil behavior between the linear-

670 elastic and nonlinear regimes. Even though more research is necessary to define robust

671 classification schemes for linear and nonlinear ground motions, we observed that including the

672 transitional motions into the nonlinear dataset reduced the variability associated with  $\kappa$  estimations

673 at our study sites.

674

675 Our results also revealed differences between  $\kappa_{0\_lin\_sur}$  (i.e.,  $\kappa_0$  corresponding to the linear-elastic  
676 regime) and  $\kappa_{0\_nl\_sur}$  (i.e.,  $\kappa_0$  for the nonlinear regime) at most sites when implementing the  $\kappa_0$ -  
677 model using ground motions classified by AP3 (which includes transitional records into the  
678 nonlinear dataset). Such differences were more prevalent among softer sites. Site parameters such  
679 as  $V_{s5}$ ,  $V_{s10}$ , and  $V_{s30}$  were used in this study to investigate the influence of soil conditions on the  
680 effects of nonlinearity on  $\kappa_0$ . Considering that high frequencies have short wavelengths, and that  
681 nonlinear soil behavior is triggered in low velocity layers more often located at a shallow depth,  
682 site proxies such as  $V_{s5}$  and  $V_{s10}$  may be more informative than  $V_{s30}$  when assessing effects of  
683 nonlinearity on  $\kappa$ . For instance, large  $V_{s30}$  values do not imply that all near-surface layers have a  
684 large  $V_s$ . The ratio of  $\kappa_{0\_nl\_sur}$  and  $\kappa_{0\_lin\_sur}$  decreases and approaches one for increasing  $V_{s5}$ ,  $V_{s10}$ ,  
685 and  $V_{s30}$ , when using the AP3 method to define nonlinear ground motion datasets.

686

687 The hypothesis posed and tested in this paper focused on the effects of ground shaking intensity  
688 on induced shear strains in sedimentary deposits and associated consequences on the attenuation  
689 experienced by seismic waves (particularly in the high frequency range). In general, we find that  
690 soil nonlinear behavior can affect estimates of  $\kappa_{r\_AS}$  and  $\kappa_0$ , but our results show that this influence  
691 is station-dependent. This is reasonable because the wave propagation of short wavelength waves  
692 is highly affected by heterogeneities in the soil or rock, local geologic structures, and topography.  
693 Moreover, the level of soil nonlinearity can be distinct at a given site (even when site  
694 parameterizations such as  $V_{s30}$  are similar and the considered intensity of ground shaking is also  
695 similar) because of the complexities of the in situ subsurface conditions (e.g., differences in  
696 velocity gradients and seismic impedance contrasts). We note that 2D/3D site effects may affect



697 ground motions recorded at six of our stations. The influence of soil nonlinearity on  $\kappa$  values  
698 computed at these stations (i.e., AICH17, CHBH13, FKSH21, IBRH20, KMMH01, KMMH12;  
699 based on the classification of Thompson et al. 2012 and Pilz and Cotton 2019) may be masked by  
700 the combined effects of wave scattering and topographic effects. Further research is necessary to  
701 evaluate the contributions of the aforementioned mechanisms on  $\kappa$  estimates at stations subjected  
702 to 2D/3D site effects. Likewise, future work should focus on collecting and analyzing additional  
703 strong ground motion data to identify local site conditions more conducive to generate significant  
704 changes in near-surface attenuation as captured by  $\kappa_0$  when nonlinear soil behavior is triggered.

705  
706 Complexities in the wave propagation phenomenon driven by scattering effects and amplification  
707 in the high-frequency range can result in negative estimates of  $\kappa_r$ . In this study, we obtained  
708 negative  $\kappa_{r\_AS}$  estimates when multiple linear decaying trends, bumps, and high frequency  
709 amplifications affected the corresponding FAS spectral shape. The identification of multiple linear  
710 decays in the high-frequency range supports previous work on the bias in  $\kappa_{r\_AS}$  associated with the  
711 selection of the frequency band. The bumps and amplifications in the high frequencies present in  
712 the FAS of some of the ground motions in our database hint that the site response may not be  
713 approximately flat within the frequency range of interest for  $\kappa_{r\_AS}$  calculation. Considering that a  
714 flat site response is one of the assumptions of the Anderson and Hough (1984)  $\kappa$ -model, further  
715 research is needed to overcome this limitation at sites where this is not the case. This work not  
716 only provides evidence of the need to understand and quantify  $\kappa$  in both, the linear and nonlinear  
717 regimes, but it also presents the limitations of the current  $\kappa$ -model when it comes to characterizing  
718 attenuation when conditions deviate from the original assumptions embedded in the Anderson and  
719 Hough (1984) model.

720

## Data and Resources

721 Accelerograms and geotechnical data are downloaded from the KiK-net network at  
722 <http://www.kyoshin.bosai.go.jp> (last accessed May 2020). The earthquake information is available  
723 from F-net network at <http://www.fnet.bosai.go.jp/top.php> (last accessed May 2020). The  
724 supplemental material to this article includes two tables and three figures. The tables provide the  
725  $\kappa_0$ -model results when using the datasets defined by AP1, AP2, AP3, and AP4, and the  $\kappa_{0\_pred}$   
726 results estimated with datasets defined by AP3. The three sets of figures presented depict the results  
727 corresponding to our 20 stations as follows:

- 728 • Surface  $PGA_{rotD50}$  against  $I_{\gamma,0}$  (i.e., results analogous to those presented in Figure 4 for  
729 MYGH10).
- 730 • Surface  $\kappa_{r\_AS}$  estimates and their corresponding  $PGA_{rotD50}$ ,  $I_{\gamma,0}$  and  $R_c$  values for selected  
731 ground motions at each study site (i.e., results analogous to those presented in Figure 7 for  
732 FKSH14 and MYGH10).
- 733 • Estimated surface  $\kappa_{0\_pred}$  and their corresponding ground shaking intensity and in situ  
734 deformation characterized by  $PGA_{rotD50}$  against  $I_{\gamma,0}$ , respectively (i.e., results analogous to  
735 those presented in Figure 11 for FKSH14 and MYGH10).

736

737

## Acknowledgements

738 The authors would like to appreciate that the National Research Institute for Earth and Disaster  
739 Prevention (NIED) provides the ground motion and site information. The authors acknowledge Dr.  
740 Adrian Rodriguez-Marek and Mahdi Bahrampouri for sharing their processed dataset. We also are  
741 thankful to Associate Editor Stefano Parolai and two anonymous reviewers for the useful  
742 comments. This work was sponsored by the U.S. Geological Survey under Grant Number

743 G19AP00058 and the NCSU Internationalization Seed Grant. The views and conclusions  
744 contained in this document are those of the authors and should not be interpreted as representing  
745 the opinions or policies of the U.S. Geological Survey.

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**Table 1.** Local soil conditions, number of ground motions per dataset, predetermined fixed-frequency bandwidth and thresholds for shear strain index,  $I_\gamma$  at all study sites.

Station	$V_{s30}$ <sup>1</sup> (m/s)	$V_{s0}$ <sup>2</sup> (m/s)	$V_{s,depth}$ <sup>3</sup> (m/s)	Hole Depth (m)	Number of linear records	Number of transitional records	Number of nonlinear records	1 <sup>st</sup> resonant frequency (Hz)	Predominant frequency (Hz)	$f_1$ <sup>4</sup> (Hz)	$f_2$ <sup>5</sup> (Hz)	$I_{\gamma,0,l}$ <sup>6</sup> (%)	$I_{\gamma,0,t}$ <sup>7</sup> (%)
AICH17	314	150	2200	101	23	27	12	4.07	4.07	12.65	25.00	0.001	0.003
CHBH13	235	220	2920	1300	139	49	11	1.78	1.78	8.95	25.00	0.001	0.003
FKSH11	240	110	700	115	148	140	26	1.51	9.98	13.97	25.00	0.001	0.003
FKSH14	237	120	1210	147	114	221	28	1.12	4.15	10.05	25.00	0.001	0.007
FKSH18	307	140	2250	100	158	103	16	2.59	5.69	8.95	25.00	0.001	0.003
FKSH19	338	170	3060	100	185	95	21	3.27	3.27	10.05	25.00	0.001	0.003
FKSH21	365	200	1600	200	60	17	8	3.90	3.90	12.65	25.00	0.001	0.003
IBRH16	626	140	2050	300	137	81	15	1.71	7.08	10.05	25.00	0.001	0.003
IBRH17	301	90	2300	510	117	177	18	0.93	9.30	13.01	25.00	0.001	0.007
IBRH20	244	180	1200	923	133	86	11	0.27	0.27	8.95	25.00	0.001	0.007
IWTH21	521	150	2460	100	39	24	6	5.27	5.27	7.38	25.00	0.001	0.003
IWTH26	371	130	680	108	79	32	11	2.12	10.17	14.24	25.00	0.001	0.003
KMMH01	575	150	1900	100	94	24	15	4.03	9.98	13.97	25.00	0.001	0.003
KMMH12	410	210	1000	123	134	34	11	3.27	8.17	11.44	25.00	0.001	0.003
MYGH07	366	130	740	142	59	39	11	0.93	8.61	12.06	25.00	0.001	0.003
MYGH10	348	110	770	205	229	132	16	0.95	10.66	14.93	25.00	0.001	0.007
NGNH29	465	150	1040	110	81	38	16	1.95	6.93	10.05	25.00	0.001	0.003
NIGH07	528	200	1600	106	29	10	11	4.12	7.08	10.05	25.00	0.001	0.003
NIGH12	553	240	780	110	29	9	11	2.00	5.00	12.65	25.00	0.001	0.003
TCGH16	213	80	680	112	112	334	35	1.27	4.81	11.27	25.00	0.001	0.007

941 <sup>1</sup> $V_{s30}$ : time averaged shear-wave velocity in the top 30 m of the soil profile

942 <sup>2</sup> $V_{s0}$ : shear-wave at the ground surface

943 <sup>3</sup> $V_{s,depth}$ : shear-wave velocity at the depth of the borehole sensor

- 944  ${}^4f_l$ : the lower frequency limit to estimate individual  $\kappa_r$
- 945  ${}^5f_2$ : the upper frequency limit to estimate individual  $\kappa_r$
- 946  ${}^6I_{\gamma,0,l}$ : the shear-strain index threshold to separate linear and transitional datasets
- 947  ${}^7I_{\gamma,0,t}$ : the shear-strain index threshold to separate transitional and nonlinear datasets

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949 **Table 2.** Ground motion datasets constructed via alternative approaches (AP1 to AP4) explored  
 950 in this study to implement the  $\kappa_0$ -model.

Approach	$\kappa_0$ _lin_sur	$\kappa_0$ _nl_sur	$\kappa_0$ _tran_sur	$\kappa_0$ _depth	$\kappa_0$ -model
AP1	Linear dataset	Nonlinear dataset	--	Borehole dataset	Equation (5)
AP2	Linear and transitional datasets	Nonlinear dataset	--	Borehole dataset	Equation (5)
AP3	Linear dataset	Nonlinear and transitional datasets	--	Borehole dataset	Equation (5)
AP4	Linear dataset	Nonlinear dataset	Transitional datasets	Borehole dataset	Equation (5)

951

952 **Table 3.** Site-specific  $\kappa_0$  values obtained from different dataset definitions at stations FKSH14  
 953 and MYGH10.

	Approach	$\kappa_0$ _lin_sur (s)	$\kappa_0$ _nl_sur (s)	$\kappa_0$ _tran_sur (s)
<b>FKSH14</b>	AP1	0.0488	0.0633	--
	AP2	0.0565	0.0638	--
	AP3	0.0500	0.0607	--
	AP4	0.0499	0.0638	0.0602
	Maximum difference	15.83%	5.10%	
<b>MYGH10</b>	AP1	0.0567	0.0563	--
	AP2	0.0568	0.0560	--
	AP3	0.0559	0.0572	--
	AP4	0.0560	0.0558	0.0575
	Maximum difference	1.56%	2.53%	

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959 **Table 4.** T-test results for  $\kappa_{0\_pred}$  values estimated with linear and nonlinear datasets defined by  
 960 AP3 (which includes records categorized as transitional into the nonlinear dataset).

Station	$V_{s30}$ (m/s)	p-value	Statistically different
		Linear $\kappa_{0\_pred}$ vs. nonlinear $\kappa_{0\_pred}$ *	
AICH17	314	10.37%	--
CHBH13	235	<0.01%	Yes
FKSH11	240	1.07%	Yes
FKSH14	237	<0.01%	Yes
FKSH18	307	2.36%	Yes
FKSH19	338	57.66%	--
FKSH21	365	47.12%	--
IBRH16	626	13.80%	--
IBRH17	301	55.92%	--
IBRH20	244	5.97%	--
IWTH21	521	9.23%	--
IWTH26	371	0.62%	Yes
KMMH01	575	0.32%	Yes
KMMH12	410	3.38%	Yes
MYGH07	366	0.04%	Yes
MYGH10	348	7.45%	--
NGNH29	465	72.74%	--
NIGH07	528	88.97%	--
NIGH12	553	66.61%	--
TCGH16	213	<0.01%	Yes

961  
 962 \*The transitional dataset is included into the nonlinear dataset (i.e., datasets following the criteria of AP3).



963 **List of Figure Captions:**

964 **Figure 1.** Comparisons between a weak and a strong ground motion recorded at FKSH14 ( $V_{s30} =$   
965 237 m/s). The  $M_w$  and  $R_e$  are 4 and 15 km for the low-intensity ground motion, while 5.1 and 15  
966 km for the high-intensity ground motion. The frequency window ([10.05, 30] Hz) applied in this  
967 plot is picked manually. The left and right columns correspond to analyses conducted on the  
968 horizontal components  $H_1$  and  $H_2$ , respectively. The color version of this figure is available only  
969 in the electronic version of this article.

970 **Figure 2.** (a) Locations of selected Japanese recording stations in this study, and (b) magnitude  
971 and distance distribution of selected ground motions.

972 **Figure 3.** Hyperbolic models fitted to observed  $PGA_{rotD50}$  and  $I_{\gamma,0}$  data at four study sites. The  $V_{s30}$   
973 for IBRH16, IBRH17, IBRH20, and IWTH21 are 626, 301, 244, and 521 m/s, respectively.

974 **Figure 4.** Surface  $PGA_{rotD50}$  against  $I_{\gamma,0}$  at MYGH10 ( $V_{s30} = 348$  m/s). The red dot-dashed lines  
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977 **Figure 5.**  $G/G_{max}$  versus  $I_{\gamma,0}$  at study sites. The  $G_{max}$  is computed from the average values of

978  $\left( \frac{PGA_{rotD50}}{PGV_{rotD50}/V_{s,0}} \right)$  for records with  $I_{\gamma,0}$  less than 0.001%. The colors represent  $PGA_{rotD50}$  values. The

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985 **Figure 7.** Surface  $\kappa_{r\_AS}$  estimates and their corresponding  $PGA_{rotD50}$ ,  $I_{\gamma,0}$  and  $R_e$  values for selected  
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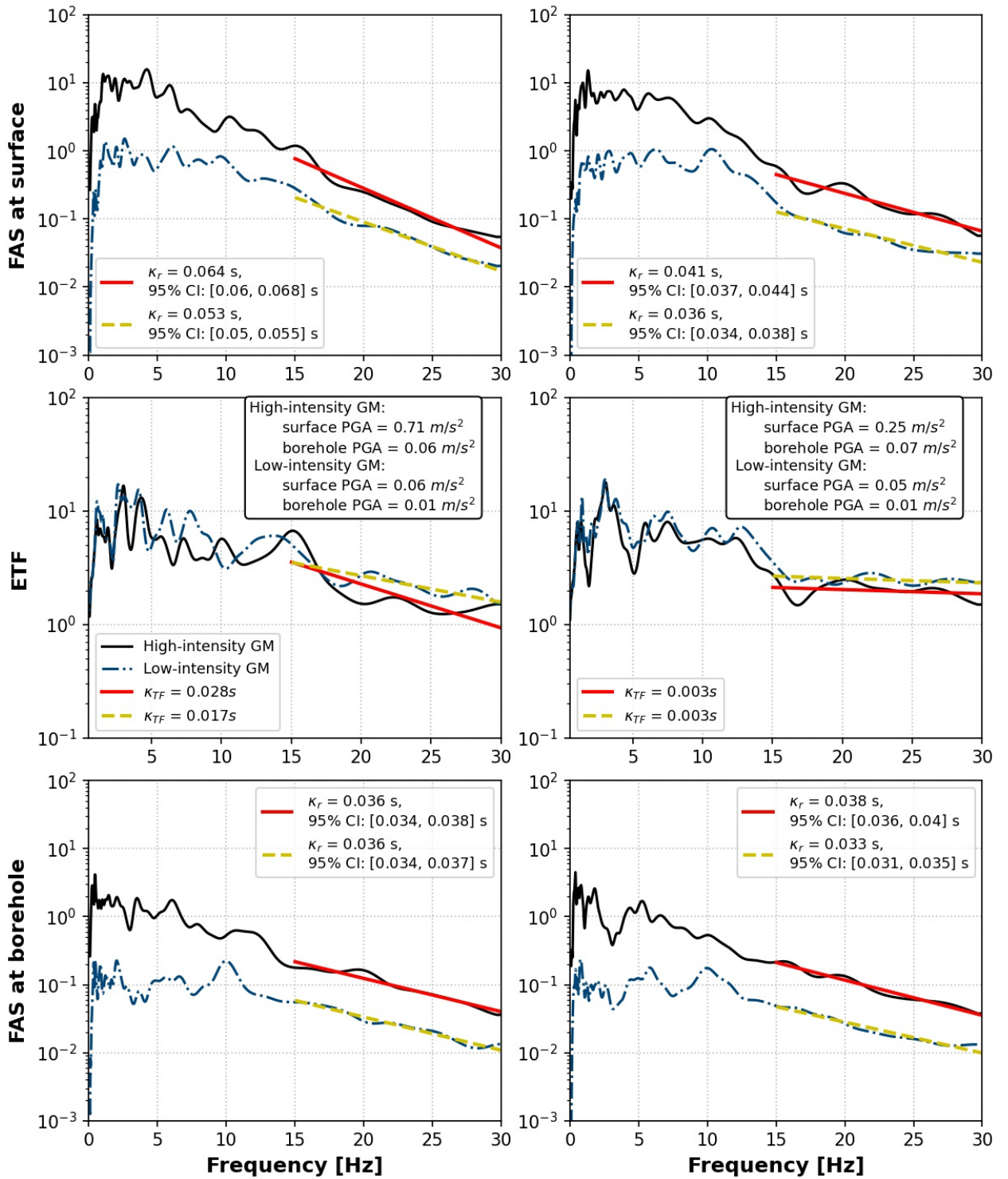
1002 **Figure 10.** Ratio of  $\kappa_{0\_nl\_sur}/\kappa_{0\_lin\_sur}$  at study sites estimated using the dataset definitions based on  
1003 AP3 (left panel) and AP4 (right panel) against to  $V_{s5}$ ,  $V_{s10}$ , and  $V_{s30}$ . The color version of this  
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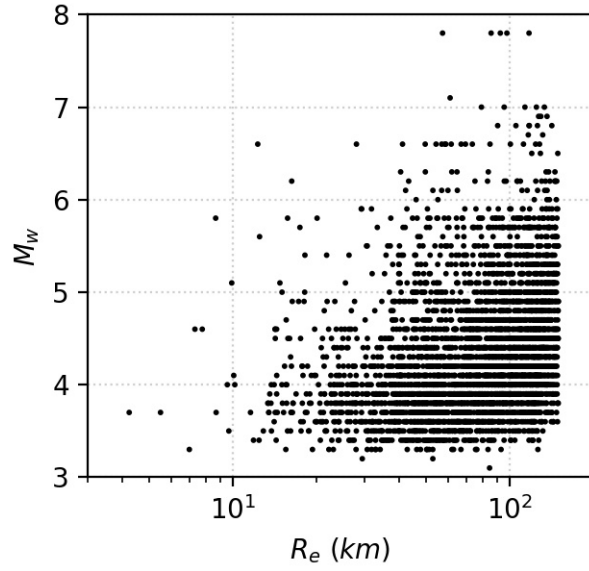
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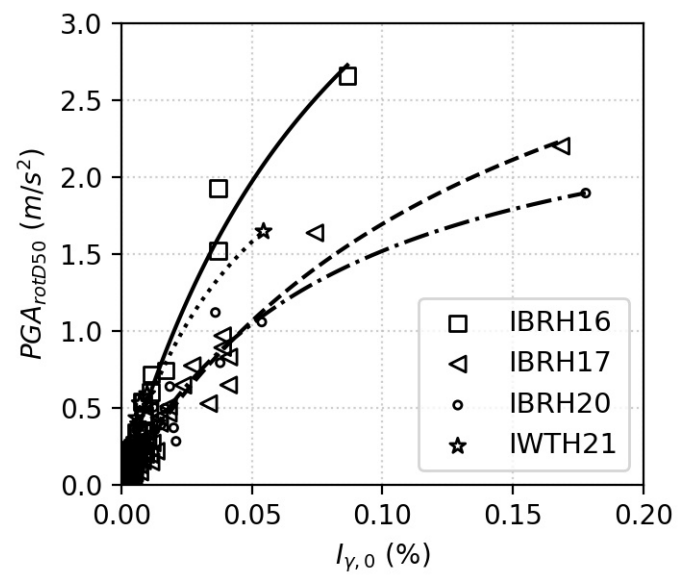


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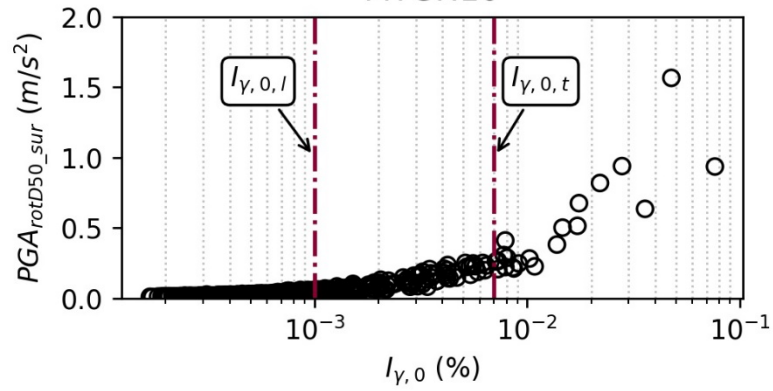
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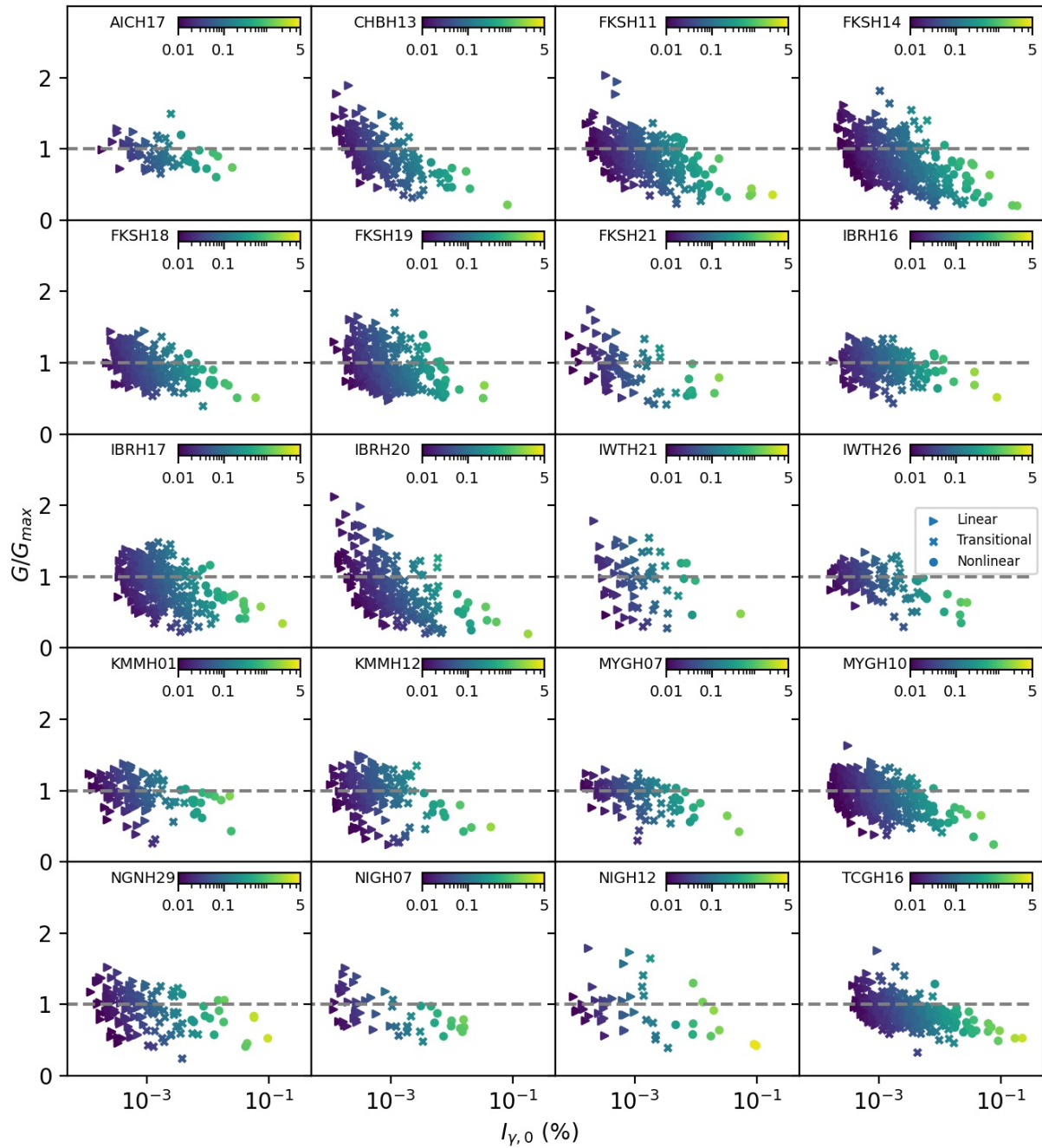
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for records with  $I_{\gamma,0}$  less than 0.001%. The colors represent  $PGA_{rotD50}$  values (in

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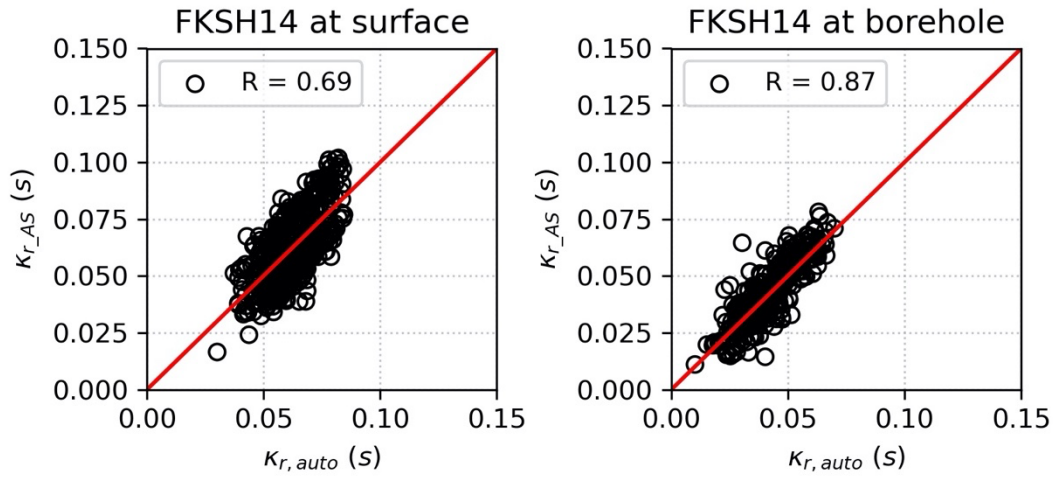
units of  $m/s^2$ ). The color version of this figure is only available in the electronic version of this

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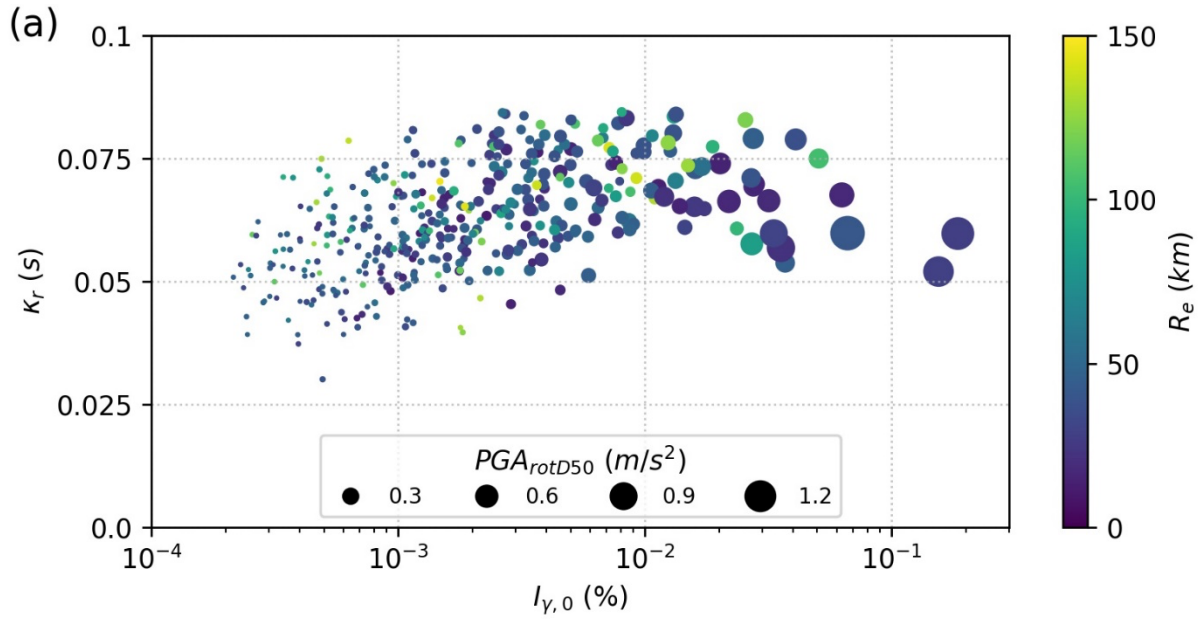
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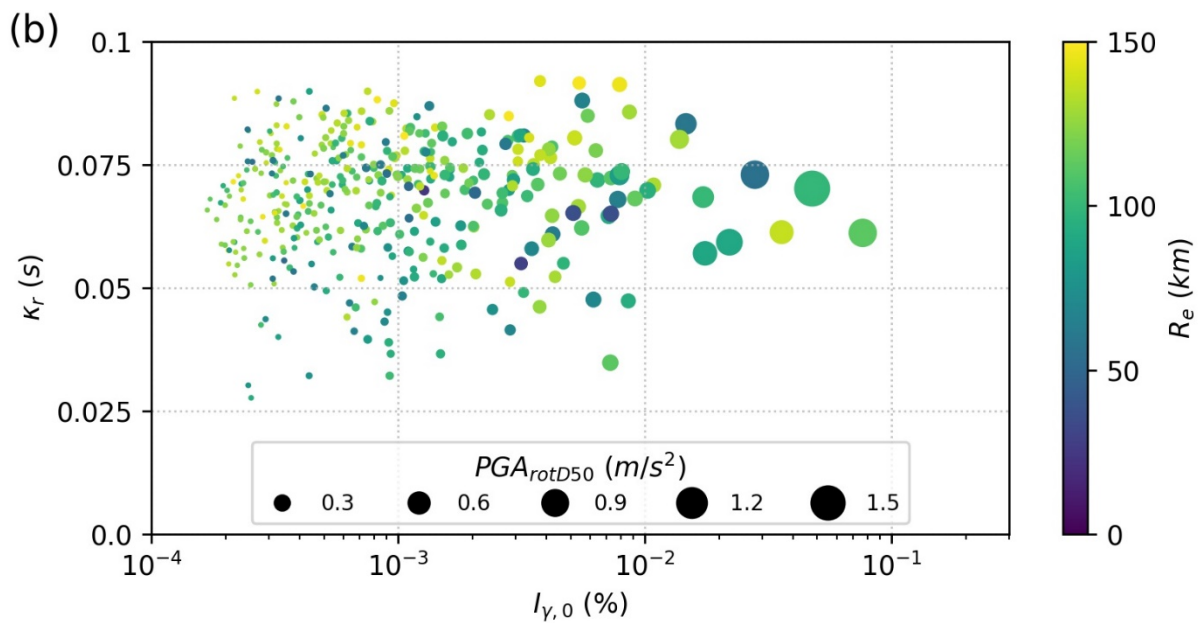
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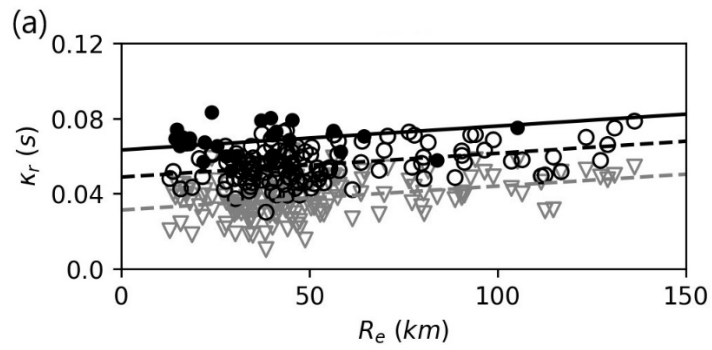
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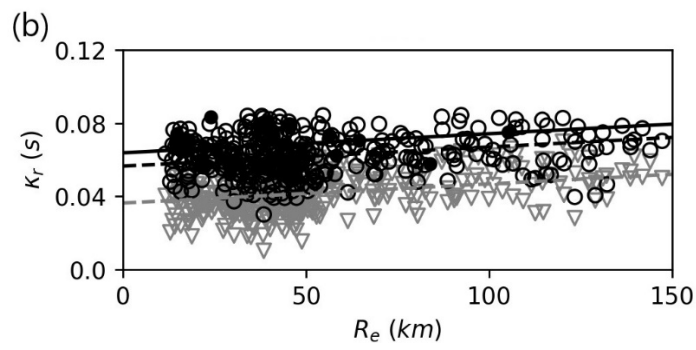
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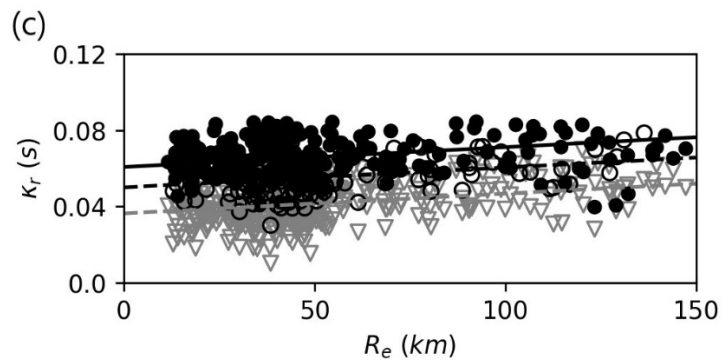
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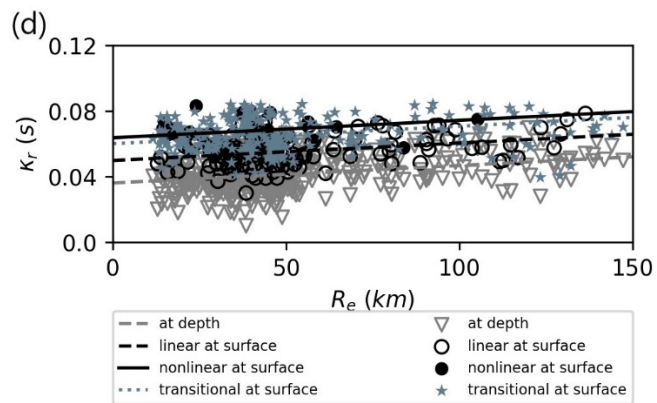
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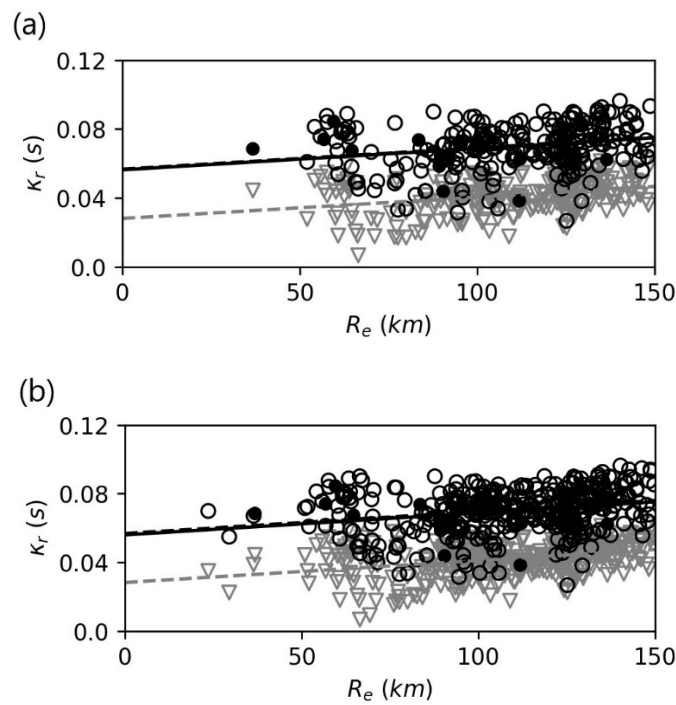


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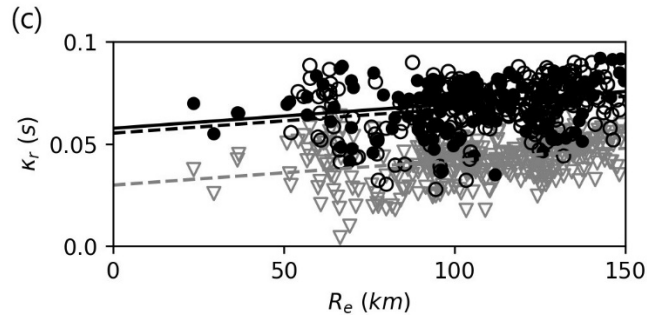
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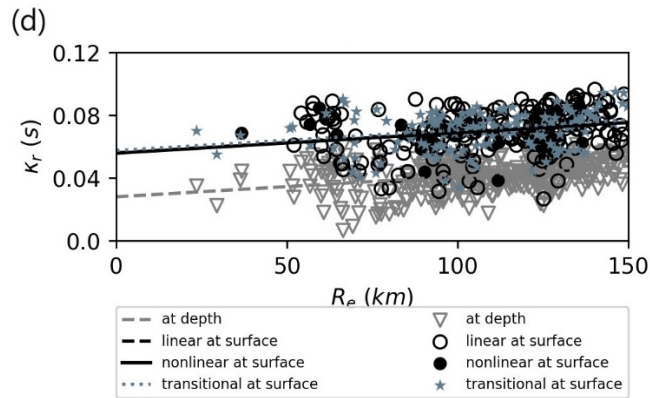
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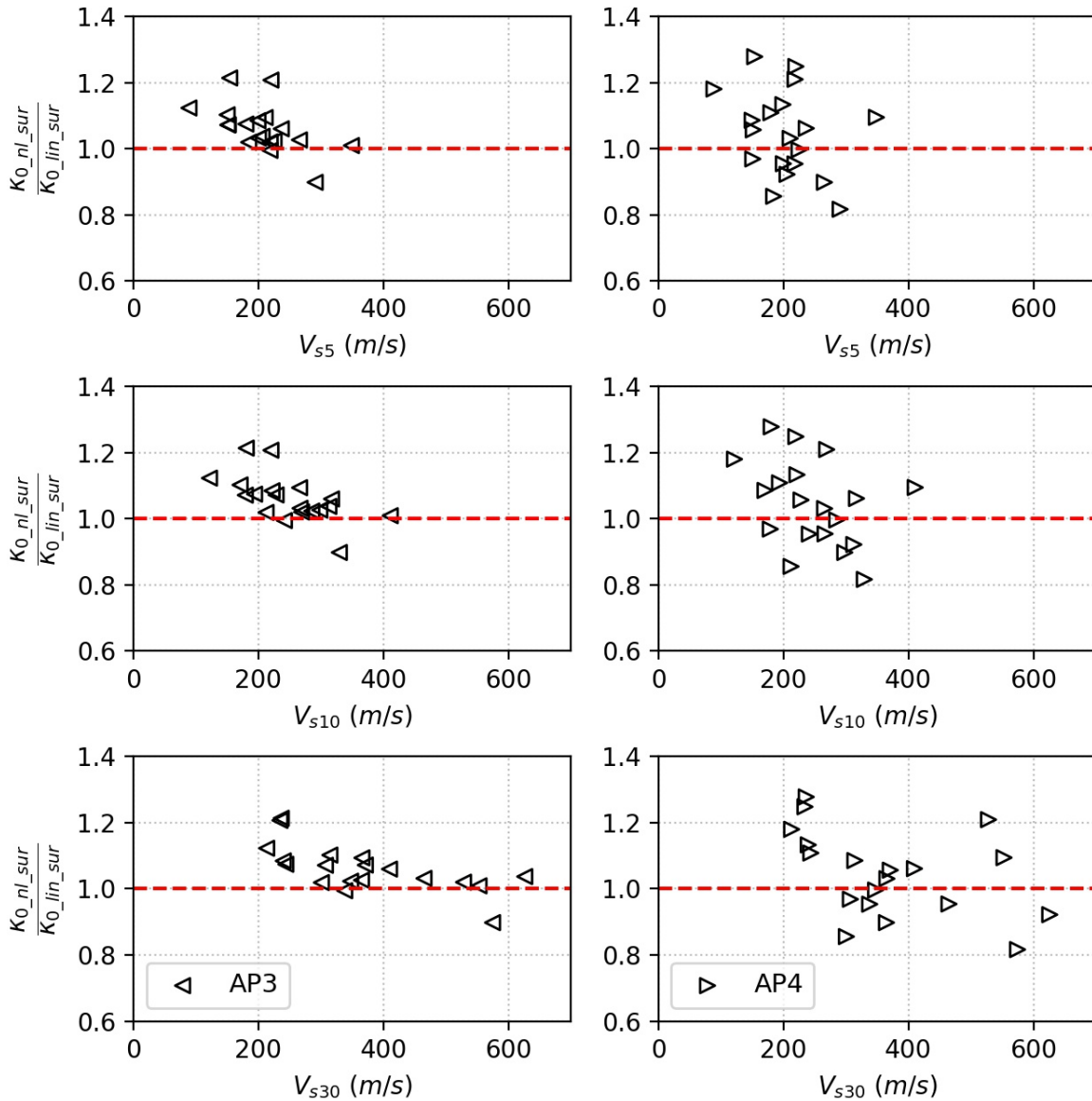


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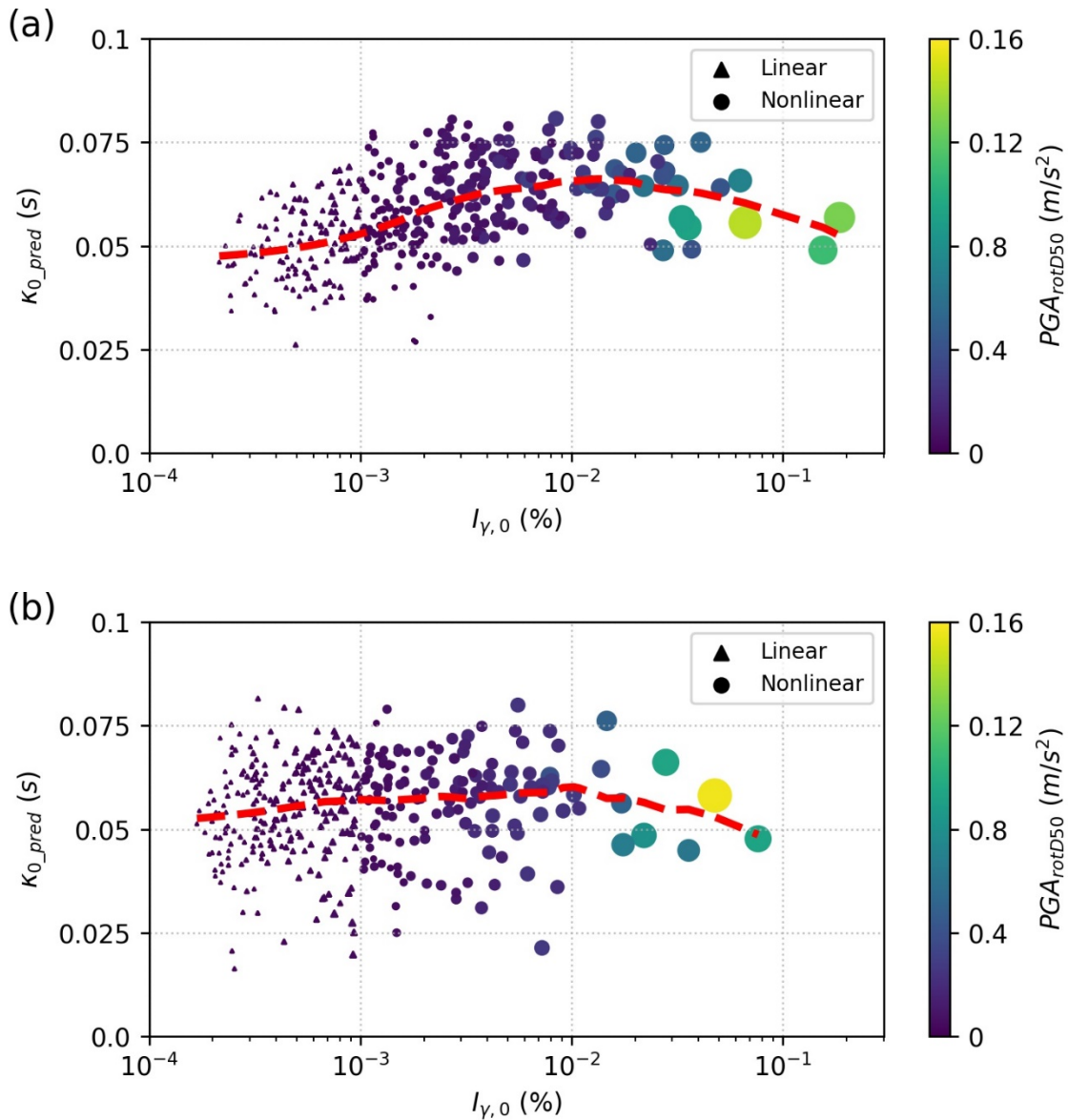
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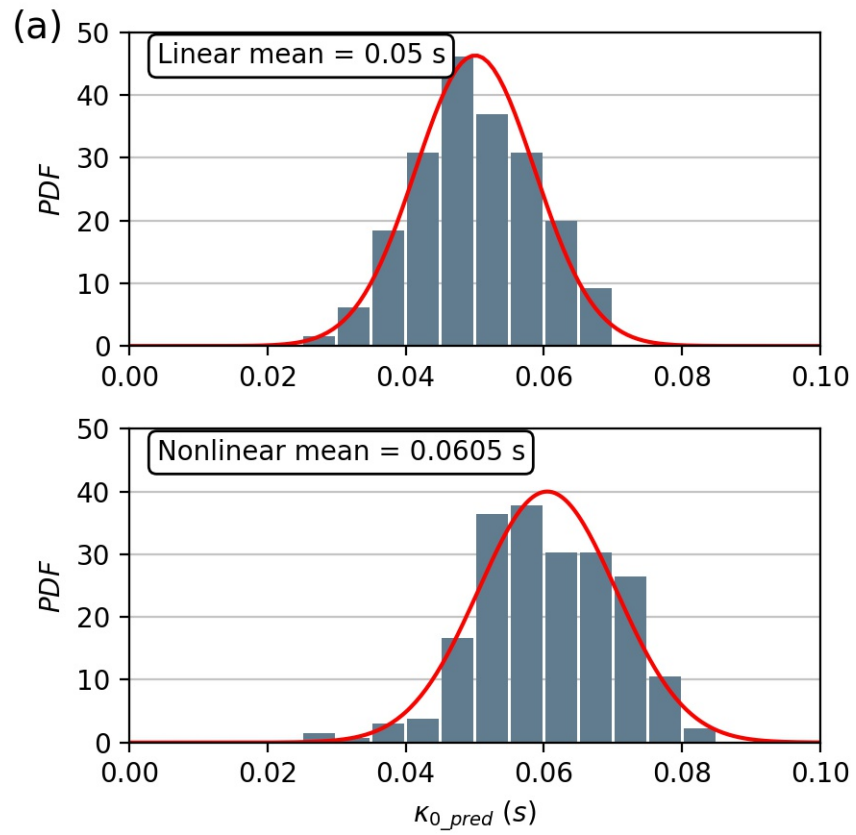
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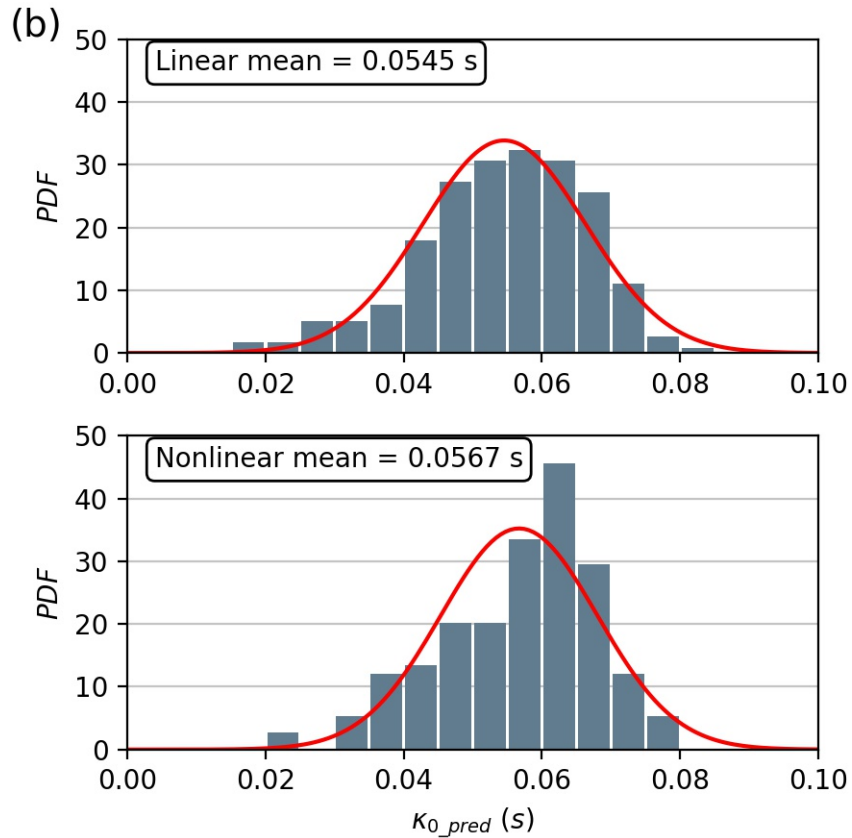
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