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Array-derived peak ground rotation rate vs. peak ground acceleration: scaling relations from seismicity induced by the Espoo/Helsinki geothermal stimulation

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Observations of ground motion in the near-field of induced earthquakes are important to assess ground shaking limits and design pumping protocols for geothermal stimulation projects, in particular near densely popluated urban areas where such zero-emission geo-energy systems can supply heat and electricity close to the consumer. Diverse seismic networks around the 2018 and 2020 geothermal stimulations in the Otaniemi district in the Espoo/Helsinki area, southern Finland, recorded the ground motions of 6-km-deep induced events at epicentral distances in the 2 to 20 km range. Key features of the seismic networks are seismic arrays consisting of 3 to 25 three-component 4.5 Hz geophones recording at 400 Hz, with interstation distances in the 50 m range. From the array seismograms of translational motion it is possible to compute rotational motion for some 200 events with local magnitudes between 0 and 1.8. The data allow the rare assessment of ground motion patterns at small distances in the cratonic low-attenuation environment of the Fennoscandian shield. Here wo focus on a systematic evaluation of the scaling relations between array-derived peak ground rotation rate (PRR) and peak ground acceleration (PGA) that have been shown to be linearly related. Array-derived motion around all three axes is computed using the ObsPy community tool implementation of Spudich and Fletcher's seismogeodetic approach. The array and subarray size controls the frequency range for which the rotational motion can be reliably estimated, hence we focus on the robustness and accuracy of the obtained PRR values. We explore the array shape dependent frequency range by a combined analysis of the quality of the PRR estimates, the quality of the linear relationship between PRR and PGA, and the wavelength-to-array-size ratio. The target frequency range is 2 – 15 Hz. We further test if the bandlimited PRR-PGA scaling differs from PGA-scaling obtained from the full bandwidth records. For narrow-band signals the proportionality factor or slope of the PRR-PGA scaling is the local slowness, which opens intriguing opportunities to probe the local velocity structure. From our data we can analyze the scaling relations and therefore consistency between the nine different component pairs of PRR and PGA motion. These results based on ratios of single peak values in a 2 s long seismogram—the S minus P time is about 1 s—are compared to local phase speed estimates from a previous analysis based on optimizing translational acceleration and vertical rotation of the full S-waveform. Data from the many small arrays are used to explore the attenuation of PRR with distance from the source. The deployment of broadband rotational

sensors and DAS systems for wavefield gradiometry analyses is anticipated to become more common in future networks; this study contributes to bridging the waiting time by providing low-tech observations of band-limited array-derived rotational motion estimates from induced seismicity for seismic engineering studies.