Raspberry Shake Instruments Provide Initial Ground-Motion Assessment of the Induced Seismicity at the United Downs Deep Geothermal Power Project in Cornwall, United Kingdom

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Abstract

Raspberry Shake (RS) seismographs offer the potential for affordable and citizen-led seismic monitoring in areas with few publicly available seismometers, especially in previously quiescent regions experiencing induced seismicity. However, their scientific and regulatory potential remains largely untested. We examine the ground motions recorded by 11 RS and one broadband station within 15 km of the United Downs Deep Geothermal Power (UDDGP) project in Cornwall, United Kingdom, to evaluate the RS network’s suitability to provide an initial ground-motion assessment of the region. To date, the British Geological Survey (BGS) has reported 232 induced events originating at UDDGP since flow testing began in summer 2020, with two events exceeding local magnitude (\(M_L\)) 1.5. Although the RS accelerometers are too noisy for UDDGP’s microseismic events, the vertical geophones are useful. Peak ground velocity observations are consistent with relevant ground-motion models, whereas peak ground acceleration (PGA) values are greater than predicted. Regional trends in the PGA levels are likely caused by path effects. Finally, RS estimates of \(M_L\) are similar to those reported by the BGS. For sparse national seismic networks, RS stations can enable a preliminary evaluation of seismic events and their ground motions.

Introduction

With its low carbon footprint, geothermal energy is a promising alternative resource to hydrocarbons, but its development has been hampered by induced seismic risks. Although small microseismic events can be a natural and common occurrence at geothermal sites, a few recent cases of larger earthquakes have alarmed the public, caused damage, and paused or halted energy development, such as in Pohang, South Korea (Kim et al., 2018) and Basel, Switzerland (Deichmann and Giardini, 2009). Knowledge of a region’s expected ground motions is key to understanding the seismic hazards associated with geothermal energy production. Thus, early microseismic events can provide an initial determination of the appropriateness of the ground-motion models (GMMs) used for the site’s planning and also reveal any unexpected regional trends in observed ground motions. In 2018, development of the United Downs Deep Geothermal Power (UDDGP) project started in Cornwall, southwest England (Ledingham et al., 2019). UDDGP targets a fault zone in the Carnmenellis granitic pluton, utilizing the natural fracture permeability and gravity to circulate water between two wells drilled to 2.5 and 4.5 km depths (Paulillo et al., 2020). Since flow testing began in summer 2020, 232 induced microseismic events in the previously quiescent region have been recorded by the British Geological Survey.

Cite this article as
Holmgren, J. M. and Werner, M. J. (2021). Raspberry Shake Instruments Provide Initial Ground-Motion Assessment of the Induced Seismicity at the United Downs Deep Geothermal Power Project in Cornwall, United Kingdom. The Seismic Record. 1, 27–34, doi: 10.1785/0320210010.
Although no ground motions have exceeded the site’s “caution” peak ground velocity (PGV) level of 0.5 mm/s (UDDGP information sheet, see Data and Resources), two events have exceeded local magnitude ($M_L$) 1.5, providing sufficient data to conduct an initial review of the region’s ground motions and to evaluate the suitability of relevant GMMs.

At present, there is only one public station from the national seismic network within 90 km of the UDDGP site, limiting the amount of available data to analyze the seismic hazard. Although both the BGS and the UDDGP operators, Geothermal Engineering Ltd. (GEL), have deployed local networks to monitor the induced seismicity, at the time of writing, the waveforms are not yet publicly available. However, GEL has provided near-by schools with seven Raspberry Shake (RS) stations in an effort to involve the surrounding communities in the geothermal project (H. Farndale, GEL, personal comm., 2021). Along with five RS deployed by hobbyists, 12 publicly available seismic stations are within 15 km of the site (Fig. 1). RSs are an affordable alternative to the more established and expensive seismic instruments available today (e.g., Anthony et al., 2019), but their suitability for seismic hazard assessment of induced seismicity for scientific and regulatory purposes has not yet been examined. In western Nepal, Subedi et al. (2020) initiated a project to raise awareness of the region’s seismic hazard by distributing RS instruments to schools and educating the local population about earthquake preparedness. During the first six months of installation in 2019, the RS network successfully recorded local earthquakes between $M_L$ 4.0 and 5.2, and an RS scale relating PGV to $M_L$ was developed. RSs have also successfully been used in combination with broadband sensors throughout the world to examine global seismic noise quieting due to COVID-19 lockdown measures (Lecocq et al., 2020). In Cornwall, two different types of RS instruments are deployed: RS1D containing one vertical geophone, and RS4D containing one vertical geophone and three orthogonal accelerometers. Anthony et al. (2019) tested three RS4D in the laboratory to investigate the instrument response. They found that although the RS performed acceptably in terms of timing errors, the...
largest limitation was the sensors’ high self-noise levels, especially those of the accelerometers. They determined that the strong-motion instruments are more suitable for recording large (magnitude > 6) local earthquakes.

Here, we investigate the ground motions recorded by the Cornwall RS network to assess its suitability in the (present) absence of data from a traditional seismic network. To assess the network’s usability and limitations, we investigate noise levels, calculate observed PGV and peak ground acceleration (PGA), evaluate GMMs, and finally estimate $M_L$ to find the magnitude of completeness and compare to the BGS $M_L$.

**UDDGP Induced Seismicity and Publicly Available Stations**

Since August 2020, the BGS has reported 232 induced earthquakes originating at the UDDGP site, spanning local magnitudes ($M_L$) between −1.3 and 1.7 and depths between 4.1 and 5.2 km (see Data and Resources). The locations and magnitudes are estimated by the BGS, using triggered event data provided by GEL’s monitoring network. At present, there are 12 publicly available stations within 15 km of the site: two RS1Ds, nine RS4Ds, and one broadband seismometer from the BGS national seismic network (Fig. 1b). Most of the RS stations are located on sedimentary rocks originating from the Devonian period, whereas the broadband and one of the RS stations are located on the granitic intrusion (BGS, see Data and Resources). The closest RS station (RAD67) is 1.4 km away (epicentral distance) from the site, and the BGS broadband (CCA1) is 6.6 km away. The combination of high noise levels and the events’ low magnitudes made the accelerometers unusable, limiting the study to only the vertical geophones. The geophones contain a single-component 4.5 Hz sensor with an electronic extension allowing usable frequencies down to $\sim$1 Hz, with a 100 Hz sampling frequency. The broadband seismometer is a 100 Hz Nanometrics Trillium (240 s natural period).

As an initial evaluation of the stations, we pick a quiescent 24 hr period when most of the instruments were active to analyze the noise levels (Fig. 2). The availability of the RS varied from station to station, most experiencing periods when they were temporarily turned off. RB30C was only active until the beginning of October 2020 and is not included in Figure 2. We first assess temporal trends of the stations’ time series by instrument...
correcting and scaling them to make their amplitudes comparable (Fig. 2a). We also evaluate each station’s power spectral density (PSD) function by splitting the instrument-corrected traces into 50% overlapping 1 hr segments, computing the PSD using multitaper (Prieto et al., 2009), and finding the average over the 24 hr period (Fig. 2b). As reference, we include the Peterson (1993) new high- and low-noise models, and the RS4D geophone self-noise curve from Anthony et al. (2019). As expected, the BGS broadband station (CCA1, black line) has the lowest noise level, seen both by the low relative amplitude in its time series and the PSD. The RS stations, on the other hand, experience various types of noise over the duration of the day. We observe similar trends for each station in all 24 hr segments that we investigated. The higher noise levels in the RS instruments are likely due to a combination of deployment in suboptimal locations near anthropogenic noise, such as machinery in buildings or train tracks, and the high self-noise levels (Anthony et al., 2019).

Ground-Motion Analysis

We estimate PGV and PGA of the vertical components for all earthquakes using the RS and broadband instruments to evaluate their suitability as an alternative to more established seismic networks. First, we analyze the signal-to-noise ratio (SNR) of the events in the frequency domain by selecting 6 s time windows encompassing the P, S, and coda waves and pre-P-wave noise windows of equal length. We remove any events with SNR below 2. The instrument-corrected time series are then filtered around the good SNR bandwidth using a two-pole, two-pass Butterworth filter and differentiated to retrieve acceleration time series. To ensure sufficient frequency coverage for usable PGV and PGA measurements, we denote \( f_1 \) and \( f_2 \) as the minimum and maximum acceptable SNR frequencies, respectively, and evaluate their coverage. PGV is generally related to the moderate frequencies, whereas PGA reflects the higher frequencies (Booth, 2007). Here, we require \( f_2/f_1 \geq 2 \) and \( 2f_1 \leq 10 \) Hz to compute PGV (Edwards et al., 2021), and \( f_2 \geq 35 \) Hz for a usable PGA measurement. To remove any records due to noise peaks, we only keep events recorded on either the broadband station (CCA1) or the closest and relatively quiet RS station (RAD67). Any extreme outliers were manually examined to see if they were noise or earthquake and removed accordingly. This resulted in 225 PGV observations for 85 events and 198 PGA observations for 83 events, spanning \( M_L \) between -1.1 and 1.7.

In ground-motion analysis, moment magnitude \( (M_w) \) is the preferred magnitude scale. Because BGS reports in \( M_L \), we use the Butcher et al. (2020) conversion developed for small earthquakes in New Ollerton, United Kingdom:

\[
M_w = 0.69 M_L + 0.74.
\]

This leads to \( M_w \) between 0.0 and 1.9.

Figure 3 shows the observed PGV and PGA values plotted against hypocentral distance. The average event depth is 4.8 km. As a reference, PGV thresholds have been included for the UDDGP cautious state at 0.5 mm/s, when humans can detect motion at 2.0 mm/s, and when UDDGP takes action at 8.5 mm/s (GEL information sheet, see Data and Resources). We also examine the two largest events \((M_L 1.6 \text{ and } 1.7, \text{ or equivalently } M_w 1.84 \text{ and } 1.91, \text{ shaded dark-gray circles and squares in Fig. 3}) \) and compare their PGA and PGV observations to three relevant GMMs. Douglas et al. (2013; hereafter, D13) developed a GMM for geothermally induced seismicity from Europe and United States, uncorrected for site, and targeting \( M_w \geq 1 \) and hypocentral distances \((R_{hypo}) < 30 \) km. Cremen et al. (2020; hereafter, C20) adjusted the Douglas GMM to create a model for \( M_L \geq 0 \) and \( R_{hypo} \leq 10 \) km, using induced events from a shale gas site (Preston New Road) and a coal mining site in the United Kingdom. Finally, Edwards et al. (2021; hereafter, E21) adjusted the Atkinson (2015) induced seismicity GMM using the Preston New Road dataset to target \( M_L \geq 0.25 \) and \( R_{hypo} < 25 \) km. We note that all three GMMs are developed for horizontal ground motions. Preferably, the vertical RS ground motions should be converted to their horizontal counterpart or the GMMs to their vertical counterpart. However, because this conversion factor is unknown for the RS and GMMs, we assume that the vertical and horizontal are equal.

As can be seen in Figure 3a, the PGV observations of the two largest events are adequately predicted by the D13 GMM, although higher than expected by the C20 and E21 models. Interestingly, the PGA observations are higher than predicted by all three models (Fig. 3b). The discrepancies could be due to several reasons. One reason could be that the region simply experiences more high-frequency content than other regions, caused by higher earthquake stress drops or alternatively less path and site attenuation. This would imply that the UDDGP site should not rely on these three GMMs for their seismic hazard assessments, and that they need a GMM adjusted specifically for Cornwall to predict the ground-motion levels adequately. Another reason for the discrepancies could be linked to our (necessary) usage of the vertical component, whereas the GMMs model horizontal ground motions. In

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DOI: 10.1785/0320210010
general, the horizontal component includes more site characteristics than the vertical (Lermo and Chávez-García, 1993). The D13 GMM does not include site effects, plausibly explaining the better match with PGV values, whereas both the C20 and E21 GMMs are adjusted to the shale gas environments they were developed for. Finally, the events’ $M_w$ are not estimated from the data directly, but instead estimated using an empirical scale developed for a coal mine environment (equation 1, Butcher et al., 2020). Thus, there will be differences in the path and site effects compared to a geothermal site targeting a granite, which could result in $M_w$ and GMM-level discrepancies.

To further evaluate the RS ground motions, we estimate station terms using the PGA observations. We choose PGA because it reflects the high-frequency content of earthquakes and site parameters, such as $\kappa$ and $f_{\text{max}}$, primarily affect the higher frequencies. Using the E21 GMM, we compute PGA intraevent residuals for all $M_L \geq 0.25$ earthquakes. E21 was developed for similar earthquake sizes and distances to the UDDGP dataset, while having a smaller sigma ($\sigma$) than D13. Intraevent residuals reflect the record-to-record variability caused by site and path effects not encompassed by the GMM (Atik et al., 2010). Figure 4a shows the intraevent residuals against distance, highlighted in the corresponding geological color. Each station’s median intraevent residual is shown in Figure 4b, grouped according to lithology. Both the smallest and largest residuals, indicating lower and higher observed PGA than expected, respectively, correspond to mud-, silt-, and sandstone stations. Thus, site effects are less likely the cause behind the station trends. One plausible explanation

![Figure 3](https://www.seismosoc.org/publications/the-seismic-record/) DOI: 10.1785/0320210010 The Seismic Record 31

![Figure 4](https://www.seismosoc.org/publications/the-seismic-record/) DOI: 10.1785/0320210010 The Seismic Record 31

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could be linked to the travel paths of the seismic waves. The UDDGP site is situated on the northeastern side of the Carnmenellis granitic pluton, which is on average 3–4 km deep and extends down to 23 km in the center (Taylor, 2007). The travel path between the UDDGP seismicity and the north-northeastern Middle Devonian mud-, silt-, and sandstone stations is mostly through sedimentary rocks (Fig. 1). In contrast, the seismic waves must travel through the granitic pluton for longer to reach the remaining stations. Because of granite’s lower-attenuation properties, the ground motions at the remaining stations are less attenuated, resulting in larger amplitudes. Furthermore, the lithological alteration caused by the Carnmenellis pluton baking and stiffening its surrounding host rock could also lead to harder rock and lower-attenuation properties.

Local Magnitude Analysis
Traffic light systems commonly use PGV or $M_L$ to monitor induced seismicity. As a final assessment of the RS stations, we estimate the $M_L$ of the UDDGP events, excluding the BGS broadband seismometer. We use the $M_L$ scale developed for the United Kingdom by Luckett et al. (2019) and currently used by the BGS:

$$M_L = \log_{10} A + 1.11 \log_{10}(R_{\text{hypo}}) + 0.00189R_{\text{hypo}} - 1.16e^{-0.2R_{\text{hypo}}} - 2.09,$$

in which $A$ is the largest zero-to-peak displacement amplitude in nanometers, and $R_{\text{hypo}}$ is the hypocentral distance in kilometers. The term $-1.16e^{-0.2R_{\text{hypo}}}$ accounts for observations at close distances ($0 < R_{\text{hypo}} < 20$ km). We convert all instrument-corrected traces to Wood–Anderson seismographs, assuming that the response of a 1.25 Hz Wood–Anderson instrument with 0.8 damping can be approximated by a 2 Hz high-pass filter (Havskov and Ottemoller, 2010). Using a 6 s time window and removing records with SNR $< 2$, we compute the $M_L$ for all RS stations. We then estimate each event $M_L$ as the median of its stations’ $M_L$, requiring a minimum of three station $M_L$ per event, and obtain 28 event $M_L$ ranging between $-0.2$ and 1.8. The reported BGS $M_L$ were computed via equation (2) using horizontal data from the local GEL network (B. Baptie, BGS, personal comm., 2021).

Figure 5a compares the $M_L$ distributions from the BGS catalog and RS stations. Unsurprisingly, the BGS $M_L$ has the lowest magnitude of completeness ($M_c$) at $\sim -0.4$. A larger $M_c$ of $\sim 0.8$ is obtained from the RS network caused by high noise levels masking the smaller events. We also include the $M_L$ distribution estimated by the closest RS station (RAD67, $R_{\text{hypo}} = 5$ km), located at similar distance as the GEL stations. Although RAD67’s $M_c$ ($\sim 0.2$) is still larger than the BGS $M_c$ and estimated using only one station, it demonstrates that deploying more RS at closer distances could lower the $M_c$. A lower $M_c$ can, for example, improve the $b$-value estimate.
and provide more useful events for developing and testing forecast models.

Finally, we compare the RS $M_L$ to the $M_L$ reported by the BGS (see Fig. 5b). Interestingly, the vertical RS geophones were able to predict similar $M_L$ to the BGS, with a median difference of $-0.01$. Theoretically, the BGS $M_L$ should be larger because the horizontal component is amplified at the site, unless the site is hard rock in which case the vertical and horizontal amplitudes are comparable (Alsaker et al., 1991). Anthony et al. (2019) found that the higher self-noise of RS can lead to larger $M_L$ to the vertical broadband (CCA1) $M_L$ and did not find RS $M_L$ relatively larger than CCA1 $M_L$ with decreasing magnitude. Another plausible explanation could be the distance correction factor in equation (2); considering the close proximity of the GEL network, these stations will have been more strongly corrected than the average RS station. Using the $M_L$, equation without the additional near-field correction might have resulted in higher $M_L$ for BGS.

**Discussion and Conclusion**

We have evaluated the performance of a network of private citizen-operated and affordable RS stations to record ground motions of induced microseismicity associated with flow testing at the UDDGP site. Notwithstanding data-quality challenges, the RS network can provide an initial determination of the applicability of GMMs and thus has significant potential for wider monitoring usage, seismic hazard assessment, and citizen–scientist involvement. Local magnitudes determined with the RS network also matched BGS magnitudes very closely. Another component to seismic monitoring is determining locations, which can be challenging without a detailed velocity model. In this study, we used the locations reported by the BGS. However, geothermal-induced seismicity tends to occur near the production well opening (e.g., Kwiatek et al., 2019), providing an acceptable proxy location for an initial earthquake assessment if locations were not available.

Limitations of the RS sensors are, however, important to characterize. RS noise levels are high compared to the publicly available broadband in the region. In addition to the high self-noise of RS instruments (Anthony et al., 2019), several of the stations were also exposed to high external noise levels, likely caused by the environments they were installed in. High noise levels are especially limiting when events are small and easily masked by interfering signals. Furthermore, permanent seismic networks rely on the quality and availability of their stations and are regularly maintained by technicians. The same level of technical support may not be available to private RS owners. The availability of the RS in Cornwall varied from station to station, but most stations had periods when they were turned off. To ensure a resilient network capable of continuous monitoring when individual stations are offline, RS networks thus need sufficiently many sensors.

Another limitation of the RS stations in this study was that only the vertical geophones were usable; because of their high noise levels, we had to discard all accelerometer data and instead assume that horizontal and vertical motions are equal. Generally, buildings are more vulnerable to horizontal motions, and thus the horizontal component is preferred for GMMs and $M_L$ analysis. Nonetheless, the RS instruments provide a useful preliminary assessment of the ground motions associated with the induced seismicity at the UDDGP site. We were able to evaluate the suitability of different GMMs for the region, examine regional trends in the observed ground-motion levels likely due to a combination of site and path effects, and estimate $M_L$ comparable to the BGS network. We conclude that an RS network is a suitable alternative for preliminary (but not definitive) seismic hazard analysis in regions lacking publicly available data from established seismic networks.

**Data and Resources**

The British Geological Survey (BGS) earthquake catalog for the United Downs Deep Geothermal Power (UDDGP) events is available through their database search at http://www.earthquakes.bgs.ac.uk/earthquakes/dataSearch.html (last accessed March 2021). The BGS geological map of Cornwall is obtained from https://ngdc.nerc.ac.uk/products/digitalmaps/dataInfo.html (last accessed February 2021). The Raspberry Shake data are available through the Raspberry Shake International Federation of Digital Seismograph Networks (FDSN) server (http://www.fdsn.org/networks/detail/AM/, last accessed March 2021). The BGS data are available from the BGS FDSN server (https://eida.bgs.ac.uk/, last accessed March 2021). All waveforms were downloaded and instrument corrected using Obspy (Beyreuther et al., 2010). Processing was carried out in MATLAB (www.mathworks.com/products/matlab, last accessed March 2021). The Geothermal Engineering Ltd. (GEL) UDDGP information sheet can be found at https://geothermalengineering.co.uk/wp-content/uploads/2020/08/Seismicity-Information-Sheet.pdf (last accessed February 2021).
Declaration of Competing Interests
The authors declare no competing interests.

Acknowledgments
The authors thank Reviewers Robert Anthony and John Douglas and Editor Keith Koper for their useful comments, which have helped improve this article. In addition, Brian Baptie, Anthony Butcher, Gemma Cremen, Jessica Irving, and Robert Myhill are thanked for their valuable help and discussion. Maximilian J. Werner would like to acknowledge Mark Vanstone’s great Twitter feed (@wmvanstone) about seismology enabled by Raspberry Shakes. This research was supported by Natural Environment Research Council (NERC) (NE/R017956/1, “EQUIPT4RISK”) and the Bristol University Microseismic ProjectS (“BUMPS”).

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