# Evaluation of site parameters to inform seismic site characterization in New Zealand

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## Abstract

Modern ground motion models typically use time-averaged shear-wave velocity to 30 m depth ($Vs_{30}$) to represent site effects. However, recent studies have shown that $Vs_{30}$ alone is not able to quantify the strong amplifications observed in sedimentary basins and propose additional parameters, such as the fundamental frequency of the site ($f_0$) and the predominant frequency peak ($f_{pred}$).

In this study, we evaluate and map the site parameters across the GeoNet network by performing horizontal-to-vertical spectral ratio (HVSR) analysis on long-term ambient vibration data and on an earthquake database developed as part of the revised National Seismic Hazard Model (NSHM). Multiple ambient vibration HVSR peaks were identified at different stations located in basins and a migration of the $f_{pred}$ from $f_0$ to higher peaks was observed in the Wellington and Canterbury basins. These parameters are included in the NSHM Site Characterisation Database, and this work will enable future research to explore advanced regional and site-specific modelling methods to better account for amplification at the local scale.

**Keywords:** site characterization; fundamental frequency of the site; predominant frequency peak; New Zealand

## 1 Introduction

Performance of the built environment during earthquakes is strongly influenced by local and regional variations in the ground conditions, with site (including topographic) effects influencing the amplitude and frequency content of ground motions. Traditional seismic hazard models approximate site/basin effects using a single site parameter such as the time-averaged shear-wave velocity to 30 m depth ($Vs_{30}$, e.g., Allen & Wald, 2009). It is well known that $VS_{30}$ is a limited proxy in capturing the full range of the site effects. Although it is statistically correlated with the deeper basin structure, it is a poor predictor of resonance at the fundamental period

($T_0$) arising from the full soil profile down to rock (e.g. Pitilakis et al., 2013; 2019; Manea et al., 2022). For such cases, alternative or additional site parameters are increasingly being explored (e.g., Z1.0, Z2.5, T0 and $T_{pred}$). $T_0$ (or fundamental frequency $f_0 = 1/ T_0$) has been proven to be a robust parameter that captures the impact of the full soil profile, including the impedance contrast between the sediment deposit and underlying rock basement (Faeh et al., 2003; Pitilakis et al., 2019). The resonance phenomenon (the fundamental frequency) is related to the bedrock depth where sharp discontinuity in velocities is found (e.g., Baise et al., 2016; Manea et al., 2017). Globally, several studies investigate the utility of a single site parameter or two complementary site parameters. Some regional models adopt the $Vs_{30}$ and the predominant period peak ($T_{pred}$) (e.g., Zhao et al., 2006; Hassani & Atkinson 2018) while other studies (e.g., Pitilakis et al., 2013, 2019; Manea et al., 2022) find that $f_0$ is the best sole site parameter for prediction, and/or Vs30 and $f_0$ are the preferred two-site-parameter combination.

In this study, we use horizontal-to-vertical spectral ratio analysis (HVSR, e.g. Nogoshi and Igarashi, 1971; Nakamura, 1989) to evaluate and map the variability of the fundamental ($f_0 = 1/T_0$) and predominant frequencies ($f_{pred} = 1/T_{pred}$) of resonance at the GeoNet seismic stations (past and present), including broadband and short period station locations. Previous characterisation of 497 GeoNet stations (Kaiser et al. 2017) did not include the broadband or short period network. Furthermore, deep soil sites were sometimes poorly characterised, given that earthquake HVSR based on limited weak motion records could not always identify long period amplification peaks. An updated site characterisation database (SCDB) for 870 GeoNet stations (Wotherspoon et al. 2022) has been developed for the 2022 National Seismic Hazard Model (NSHM, Gerstenberger et al. (2022)) update, many of these newly added stations are located on rock. The new ambient noise HVSR analysis significantly improves the quality of the $T_0$ measurements in the SCDB, allowing for future progress in investigating the influence of site response and how well single or multiple site parameters can represent site effects.

# 2 Data and methods

To evaluate the fundamental frequency at all the three-component seismic stations across New Zealand, the Geonet broadband network (GNS Science, 2021) station data streams were used to select long term ambient vibration data (100 days during the lifetime of each station). For strong-motion sensors, low magnitude events (Mw<4.5) data were used as no complex source features or non-linear site effects are usually seen in their spectra. The distribution of the Geonet seismic stations across NZ and their characteristics is presented in Figure 1. A subset of records, at hypocentral distances less than 300km, from the strong motion database built within the NSHM revision project, was used to evaluate the variability of the predominant frequency. It comprises all the records for events with Mw>4 that occurred between 2000 - 2021 (NZDB, Hutchinson et al., 2021; 2022) and an expansion of the previous New Zealand Strong Motion Database (Van Houtte et al., 2017). A complete description of the meta-data is presented in the Hutchinson et al. (2022) and Wotherspoon et al. (2022). The event distribution across NZ together with their type classification is also presented in Figure 1.

To extract the $f_0$ and $f_{pred}$, we used the horizontal-to-vertical spectral ratio (HVSR, e.g. Nogoshi and Igarashi, 1971; Nakamura, 1989) based on the most recent methodologies (e.g., Cox et al. 2020; Cheng et al. 2020) for both ambient vibration and earthquake data. Before processing, any offset and linear trend (that typically affects broadband recordings) was removed by band-pass filtering between 0.1 and 30 Hz. The ambient vibration signals were then split in sub-windows of 100 seconds length, while a migrative window was used for earthquake data, and each sub-window tapered with a 10% cosine taper before performing the Fourier spectral ratios. Spectra were subsequently smoothed using the Konno and

Ohmachi (1998) algorithm with a bandwidth parameter of 60 (in log units), and the results from all windows are averaged for each seismic station separately assuming lognormal statistics.

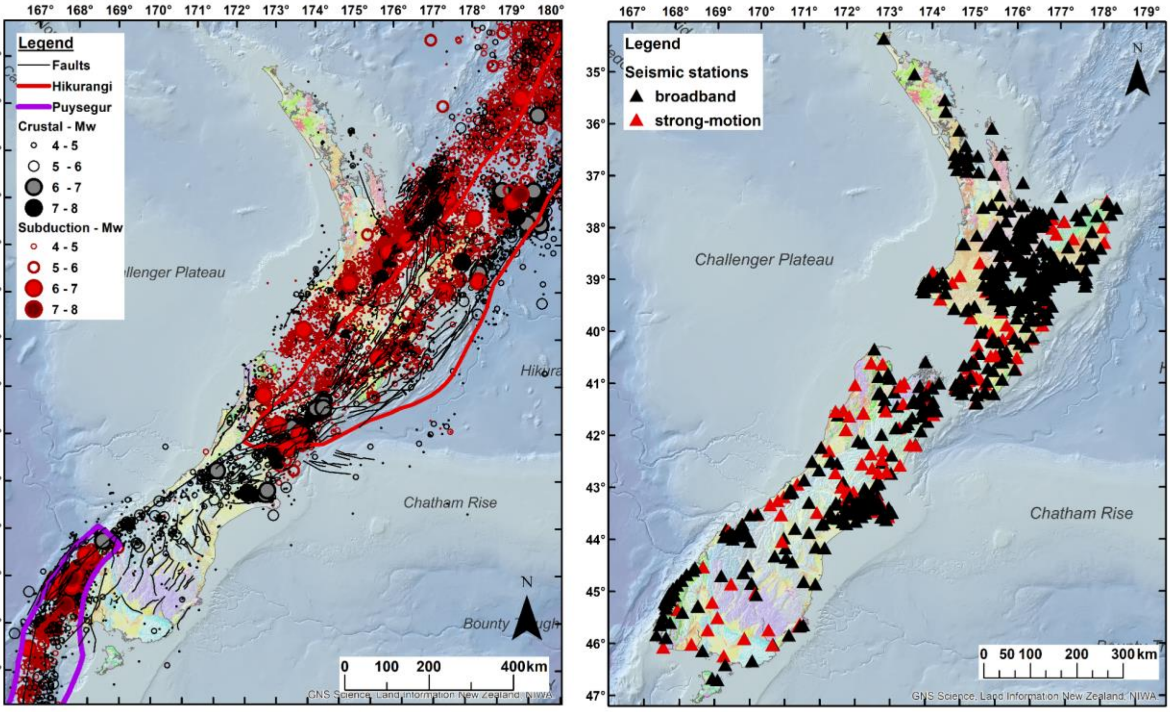


***Figure 1.*** *Location of the (left) analysed earthquake epicenters and (right) Geonet seismic stations on the geological map. For a detailed legend of the geological map, see GNS Geological Map of New Zealand 1:250 000 (1st edition). The community Fault Model V1.0 (Seebeck et al., 2022) is represented with black lines, while the two subduction zones are in red - Hikurangi and purple - Puysegur (Thingbaijam et al., 2022).*

A screening process was undertaken to ensure that any peaks identified in the HVSR curves, following the SESAME (2004) guidance, were representative of the response of the soil profile above the key rock impedance contrast (Wotherspoon et al., 2022).

When multiple peaks were present in the HVSR data at a single site, the characteristics of each peak were assigned to each of the parameters described here following the individual guidance for each. Where multiple peaks were present, which is representative of multiple impedance contrasts within the profile, the peak representative of the fundamental of the profile above the key impedance contrast was reported. If there was no peak representative of f0 in the HVSR data at a site that was expected to have rock at or near the ground surface, a f0 value of 20 Hz was assumed.

# 3 Results

## *3.1 Evaluation of the fundamental frequency of resonance*

The HVSR of ambient vibrations was computed for each seismic station to identify the fundamental resonance frequency ($f_0$) of the site. The variability of the HVSR curves is presented in Figure 2 for stations located in the Wellington and Canterbury regions.

In Wellington, stations located in variable ground conditions around the region which is reflected in the range of HVSR curves and amplification peaks.  In Canterbury, many stations are located on significant thicknesses of sediment forming the Canterbury Plains, and show fundamental frequencies of 0.14 - 0.5 Hz, consistent with the previous Canterbury regional studies of Wotherspoon et al. (2016) and Stolte et al. (2022). The variability of the $f_0$ parameter (from HVSR) at national level is presented in Figure 3(a), while its regional spatial distribution in Wellington and Canterbury regions can be seen in Figure 3 (b, c).

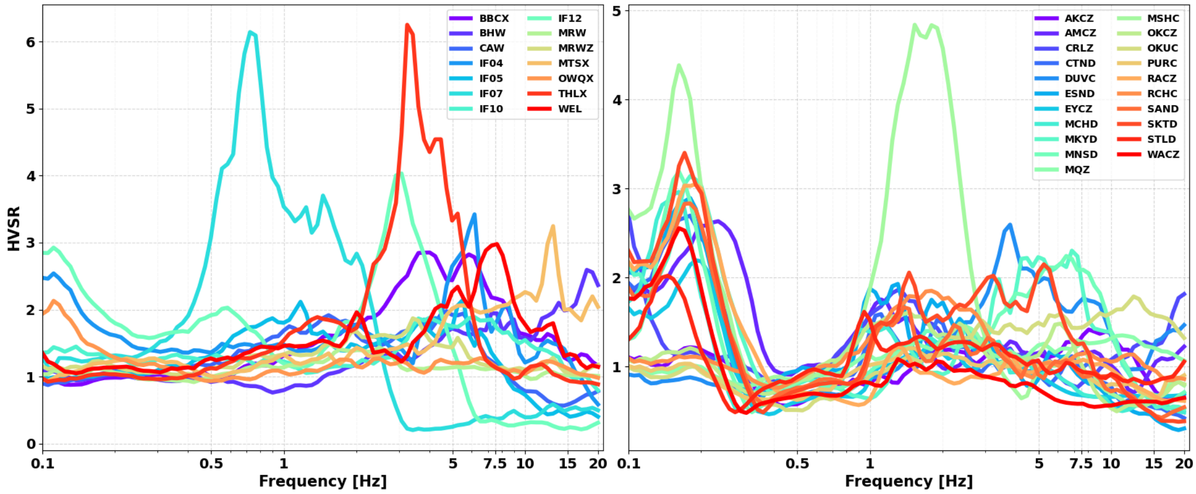


*Figure 2. The variability of the HVSR spectral ratios of ambient vibrations at each seismic station in (left) Wellington and (right) Canterbury.*

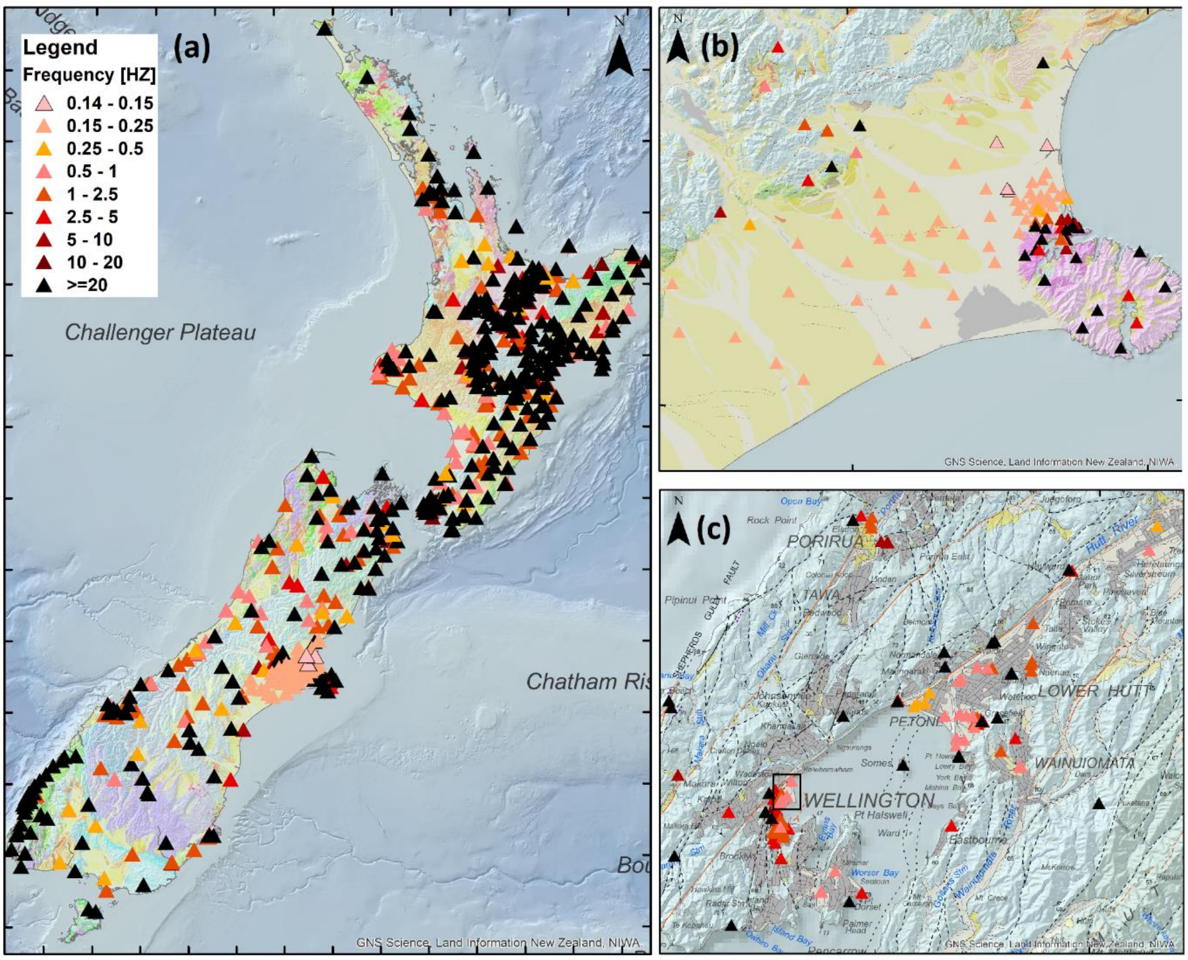


*Figure 3. The variability of the fundamental frequency of resonance (a) along New Zealand territory and its regional spatial distribution in (b) Canterbury and (c) Wellington, black rectangle - CentrePort area.*

For Wellington city (Figure 3, b), the $f_0$ becomes lower in the CentrePort area where a deepening of the bedrock was observed (e.g., Hill et al., 2022). The lowest $f_0$ is present consistently across the Canterbury plains with values consistent with the regional classification study of Stolte et al. (2022).

At several stations multiple ambient vibration based HVSR peaks were identified (Figure 2) and attributed to the complex local geological structure. The earthquake HVSRs show a migration of the $f_{pred}$ from $f_0$ to higher modes mostly at stations located in the Wellington and Canterbury basins. The retrieved $f_0$ was interpreted in the SCDB along with existing geological and geophysical information at a given station, and a quality estimate was given using the Kaiser et al. (2017) scheme. The SCDB also contains other site parameters (e.g., standard deviation of $f_0$, flag for the reference sites, the resonant period of strong topographic amplification peaks at rock sites) extracted from the HVSR curves.

## 3.2 Evaluation of the predominant frequency

The HVSR curves were computed on earthquake data at each seismic station and their values at representative stations located in Wellington and Canterbury regions are presented in Figure 4 and 5. In Wellington, $f_0$ and $f_{pred}$ are typically similar, but with some small shifts that can be observed in Figure 4. Where strong (and known) amplification effects occur associated with the soil-bedrock contact (e.g., TEPS, NBSS, PIPS) the values are relatively consistent. At other stations, a broader flatter peak is observed (e.g., WEMS and VUWS).

In Canterbury, the strong motion earthquake HVSR does not typically identify the fundamental resonant peak at very low frequencies (0.14 - 0.2 Hz) at deep soil sites (e.g., KPOC, MPSS, REHS and RHSC). This is mostly due to the low frequency amplitude content of the major Canterbury events (Bradley, 2012). The predominant frequency occurs between 1 - 5 Hz and is associated instead with variable thickness of soft or loose sediment in the near-surface deposited (above the Banks Peninsula Volcanics) by the braided river systems of the Canterbury Plains. The stations TOKS and GOVS are located on rock or shallow marine sediments in the Ports Hills region and exhibit distinctly different characteristics and $f_0$ and pred values that are consistent (Figure 5).

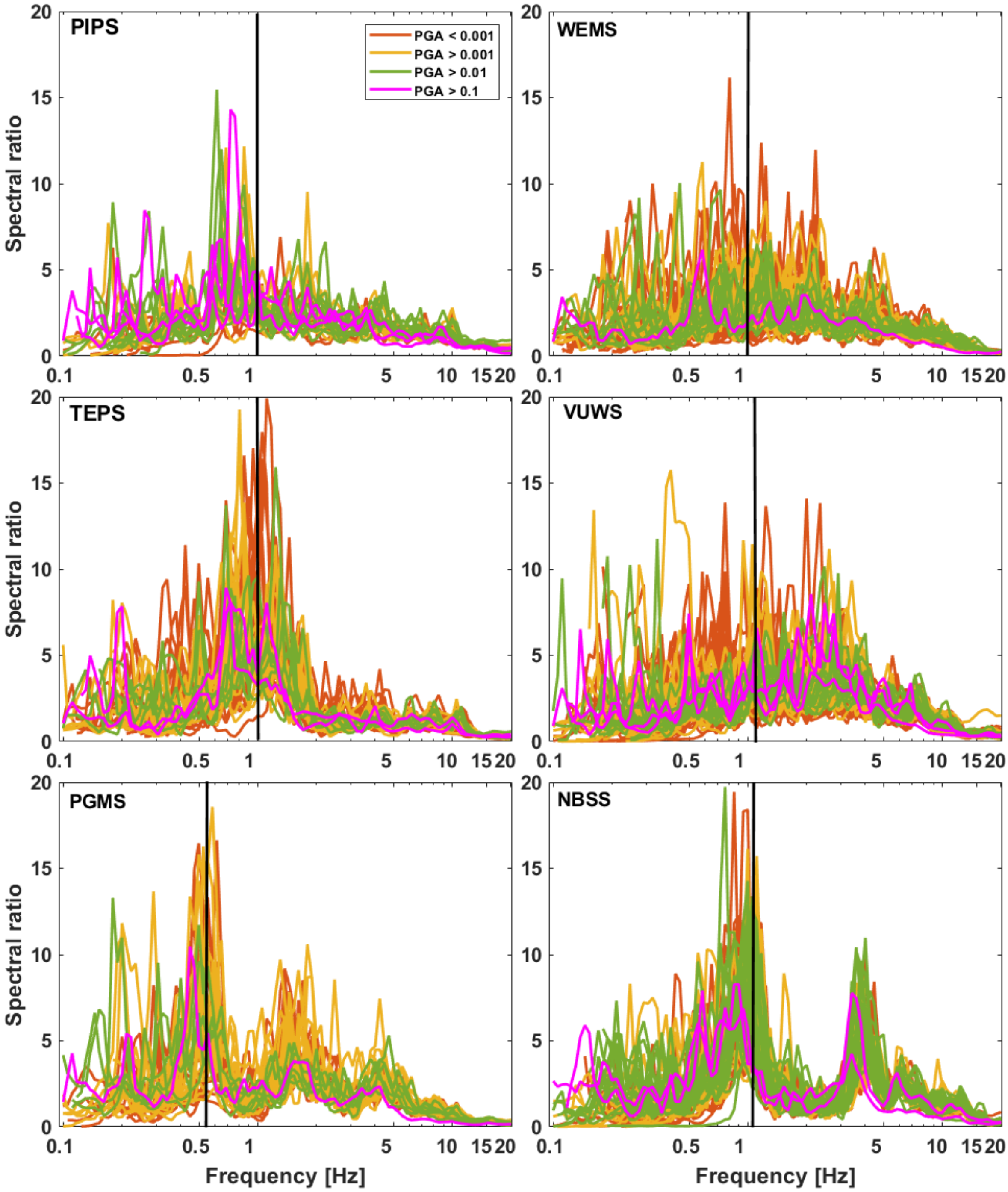


*Figure 4. HVSR curves computed for all the events in the NZDB seismic database at six representative stations in the Wellington region. The HVSR curves were classified based on the PGA values [g]. The black vertical line is the $f_0$ extracted from the final interpreted SCDB.*

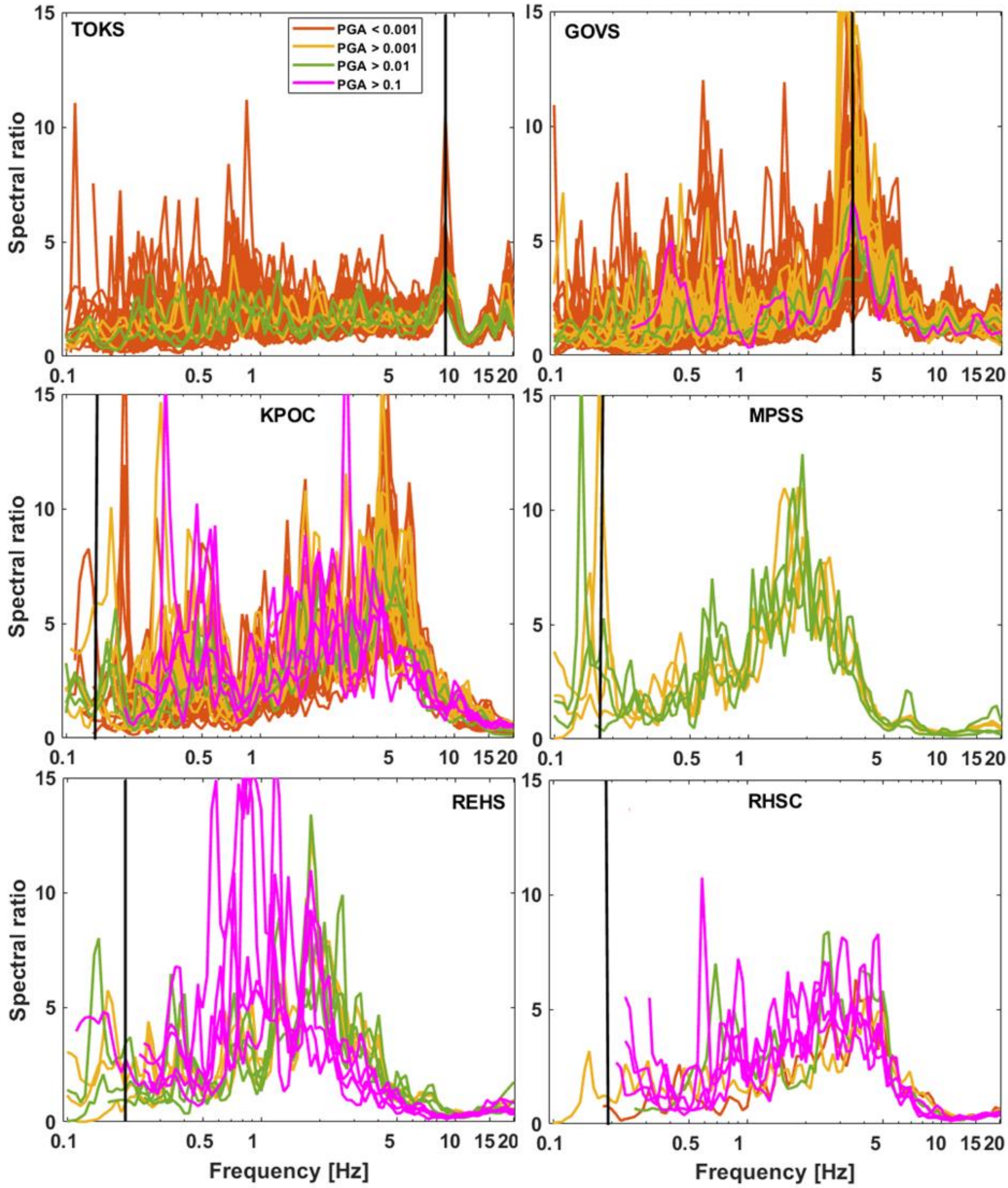


*Figure 5. HVSR curves computed for all the events in the NZDB seismic database at six representative stations in the Canterbury region. The HVSR curves were classified based on the PGA values [g]. The black vertical line is the $f_0$ from the final interpreted SCDB.*

# 4 Conclusions

In this study, we evaluate and map the $f_0$ and $f_{pred}$ site parameters across the GeoNet network by performing horizontal-to-vertical spectral ratio (HVSR) analysis on long-term ambient vibration data and an earthquake database developed as part of the 2022 National Seismic Hazard Model (NSHM). The number of sites increased from 497 to 870 between the 2017 (Kaiser et al., 2017) and our 2022 analysis, with the inclusion of short period and broadband seismometer stations of the national network. At several stations multiple ambient vibration based HVSR peaks were identified and attributed to the complex local geological structure. The earthquake HVSRs show a migration of the $f_{pred}$ from $f_0$ to higher modes mostly at stations located in the Wellington and Canterbury basins.

Summary and interpretation of the $T_0$ peak ($1/f_0$) is included in the 2022 NSHM Site Characterisation Database along with estimates derived from previous and recent regional studies (Wotherspoon et al., 2022). Overall, $T_0$ is the most well-constrained parameter, with almost half of the database based on the highest quality measurements. The number of stations with a high quality significantly improved from around 100 sites in 2017 to over 400.

This work will enable future research to explore advanced regional and site-specific modelling methods to better account for amplification at the local scale.

# 5 Acknowledgments

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