Application and development of ambient noise methods for direct prediction of site amplification at high spatial resolutions in New Zealand sedimentary basins

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ABSTRACT

Ambient-noise methods, and the horizontal-to-vertical spectral ratio (HVSR), whether from earthquakes (eHVSR) or mircrotremors (mHVSR), have gained much popularity in the field of site response over the last decade. These methods can be used either for direct prediction or to inform the velocity structure utilized in more conventional site response analyses. This paper describes a field study and subsequent analyses undertaken in the Lower Hutt sedimentary basin of New Zealand. The field study involved collecting 50 ambient-noise or microtremor measurements across the entire basin over the same time window that microtremor measurements were being recorded at strong-motion stations in the basin for use as reference stations. Additionally, microtremor array measurements (MAM; involving ~24 ambient-noise measurements per site) and multi-channel analysis of surface waves (MASW) were conducted at five sites to better quantify deep and shallow velocity structure of the basin. In total, microtremor data were collected at 154 locations. This paper focuses on the use of the microtremor data collected for direct prediction of site response in the sedimentary basin. The hybrid standard spectral ratio approach is tested in this region. A rigorous validation study was performed at strong motion stations at which microtremor measurements were made for use as reference basin sites in the hybrid spectral ratio method. The prediction accuracy and uncertainty of the method, when using synchronized versus unsynchronized data between the reference basin sites and temporary target sites, are compared. The hybrid spectral ratio method predicts well the observed site amplification between nearby, deep basin sites for $f < 5$ Hz, when synchronized data are used. Predictions around the fundamental frequency of the basin (corresponding to periods of 1- 2 seconds) worsen when unsynchronized data are used due the influence from environmental and anthropogenic factors on microtremor amplitudes. Finally, the method is used to predict the site response, relative to a rock reference site, at all basin sites at which synchronized temporary microtremor data were collected. Early efforts to spatially interpolate the observations and predictions are discussed.

Keywords: microtremor, HVSR, ambient-noise, site amplification, basin effects

1 INTRODUCTION

Several recent studies have shown the potential usefulness of microtremor methods, which utilize the earth's ambient vibrations, in site response applications. These studies include those that seek to improve: 1) site and basin shear wave velocity models (e.g., Stolte et al., 2022; Hallal and Cox, 2022), and 2) estimates of site response through direct prediction using methods such as the horizontal-to-vertical spectral ratio (HVSR; e.g., Esteghamati et al., 2022; Pinilla-Ramos et al., 2022; Wang et al., 2023) and the hybrid standard spectral ratio (hSSR; e.g., Perron et al., 2018; Perron et al., 2022).

A field testing campaign was performed to collect microtremor data throughout the Lower Hutt sedimentary basin near Wellington, the capitol city of New Zealand. The purpose was to improve the seismic site characterization data using MAM, MASW and HVSR, and estimate the site response at a reasonably high spatial resolution using HVSR-based methods and the hSSR method. This paper focuses on the application and interrogation of the hSSR method.

The fundamental assumption of the hSSR method is that the ratio of horizontal Fourier amplitude spectra (FAS) from microtremor data between two sites within the same basin is approximately equal to the ratio of FAS from earthquakes for the same two sites (Perron et al., 2018). Given this assumption, the earthquake standard spectral ratio (eSSR) observed at a basin site, relative to a reference rock site, can be used to estimate the eSSR for a temporary basin site at which no earthquakes have been recorded (only microtremor data), relative to the same rock reference site.

The hSSR has been shown to predict the observed eSSR with reasonable accuracy in other regions of the world. However, to validate the hSSR method in this region, it was first applied to the strong motion stations at which microtremor data were collect. Given that there were generally more than one deployment (on different days) at each SMS, it was possible to check the influence of using synchronized data versus unsynchronized microtremor data between the reference site and the target site.

2 FIELD TESTING CAMPAIGN

The field testing took place on 16-20 January, 2023, and involved eight researchers. The objectives were to collect data to improve the seismic site characterization at SMS within the basin, refine the existing 3D velocity model for the region (Boon et al., 2010), and apply the hSSR method to estimate the site response across the basin. For improving the seismic site characterization, MAM and MASW were performed at five sites, including three SMS (SOCS, LNBS, and NBSS; see Fig. 1) and two golf courses where large arrays were deployed to characterize the deep sediments. At each site, one MASW line and two to three MAM arrays were deployed. A total of 96 microtremor measurements were made as part of these MAM arrays and these measurements are used to estimate site period using microtremor HVSR (mHVSR) in this paper.

The main objective of the field campaign, and the focus of this paper, was to apply the hSSR method to estimate site response within the sedimentary basin at locations where earthquakes have not been recorded. As described in Perron et al. (2018), the method involves synchronically (i.e., at the same time) measuring microtremor data at a permanent earthquake recording station within the basin and at a target basin site at which no earthquake recordings exist. Previous studies have found that the microtremor data from continuously recording accelerometer strong motion stations are not of sufficient quality to robustly calculate mHVSR. For this reason it was necessary to deploy broad-band seismometers at the reference basin sites (i.e., the SMS) while data was collected at nearby temporary target basin sites. Given personnel limitations, a maximum of four basin reference sites could be used while four other group members recorded data at the temporary target sites.

Fig. 1 shows the location of all nine SMS used as reference basin sites for the hSSR method, as well as all microtremor measurements for temporary target basin sites and MAM array. All points are color-coded by fundamental period, based on mHVSR ($T_{0,mHVSR}$). For each temporary measurement, generally the closest four SMS were used as the reference sites. For example, for locations closest to the waterfront (see Fig. 1) the reference SMS were: PVCS, PGMS, SEVS, and LRSS.

In general, the seismometers were deployed at the reference stations (groups of four sites) for periods of four hours. Over each four hour period, as many temporary deployments as possible, of 45-60 minutes each, were performed at the intermediate basin sites by the remaining four group members. The instruments used were 120 second Nanometrics Trillium Compacts for the temporary points and 20 seconds Trillium Compacts for the reference points.

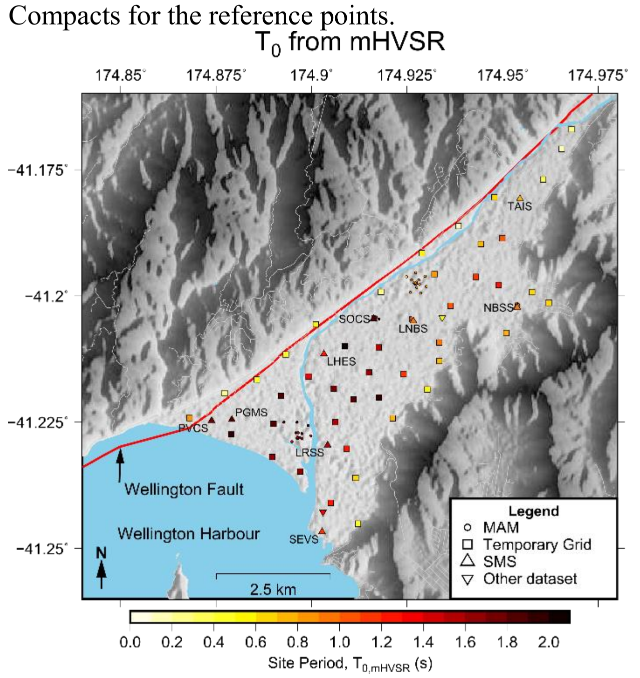

Fig. 1. Map of the Lower Hutt region showing the location of all microtremor field measurements for hSSR, mHVSR, and MAM. The nine reference SMS used for the hSSR method are labeled.

3 FUNDAMENTAL PERIOD ESTIMATES AND THE CURRENT 3D GEOLOGIC MODEL

As mentioned above, estimates of fundamental period from mHVSR for all microtremor measurements are presented spatially in Fig. 1 in which symbols are color-coded by $T_{0,mHVSR}$. The patterns of fundamental period are consistent with existing knowledge of the basin geology and geometry (Boon et al., 2010). As the basin widens downstream, towards Wellington Harbor, it deepens and $T_{0,mHVSR}$ estimates increase. At its maximum depth (and width), at the south-west corner along the harbor, the sediment thickness is about 300 m and the $T_{0,mHVSR}$ estimates are approximately 2 s. In this area, the basin is approximately 4.8 km wide. The total basin length is approximately 10 km. The dip of the Wellington fault (surface trace shown in Fig. 1) is nearly vertical, which is consistent with the rapid change in T_0 over short distances. As shown in Fig. 1, all measurements on or near the surface trace of the fault have short periods (< 0.5 s) suggesting relatively shallow sediment depth over the complex step-like geometry around the fault surface trace. Just 200 m east of the surface trace, $T_{0,mHVSR}$ estimates increase to as long as 2 s (e.g., at PVCS in Fig. 1).

4 METHODOLOGY FOR THE HSSR

As mentioned in previous sections, the hSSR method, developed in Perron et al. (2018), is founded on the hypothesis that the ratio of horizontal earthquake FAS (eFAS) between two basin sites can be approximated by the ratio of synchronized horizontal microtremor (i.e., noise) FAS (nFAS) for the same two sites. Mathematically, this is expressed as:

$$\frac{eFAS_i}{eFAS_j} \sim \frac{nFAS_i}{nFAS_j} \quad (1)$$

Where i represents the temporary target basin site at which earthquakes have not been recorded and j represents the reference basin site at which earthquake observations exist. To quantify the full site response, it is common to calculate the ratio of eFAS from a basin site to that of a reference rock site. This is commonly referred to as the earthquake standard spectral ratio (eSSR), and is expressed as:

$$eSSR_{i/r} = \frac{eFAS_i}{eFAS_r} \quad (2)$$

Where r represents the reference rock station, outside of the basin, at which earthquakes have been recorded. In Equation (1), it is desirable to express the eFAS ratios relative to the rock reference site, r. To do so, both the numerator and denominator of the left side of the equation can be divided by $eFAS_r$ to obtain Equation 3:

$$\frac{eFAS_i/eFAS_r}{eFAS_j/eFAS_r} \sim \frac{nFAS_i}{nFAS_j} \quad (3)$$

Which can be rewritten as:

$$\frac{eSSR_{i/r}}{eSSR_{j/r}} \sim \frac{nFAS_i}{nFAS_j} \quad (4)$$

Rearranging, we can solve for the desired $eSSR_{i/r}$ to estimate the full site response for site i, at which no earthquake observations exist. This term is referred to as the hybrid spectral ratio (hSSR), as it is a hybrid of the eSSR observed at one basin site and the nFAS observed at both basin sites. The ratio of nFAS is referred to as the noise spectral ratio (nSSR). Given all of this, the hSSR for the target site and a given reference basin site, j, can be written as:

$$hSSR_{i/j,r} = eSSR_{j/r} \times nSSR_{i/j} \quad (5)$$

To estimate the uncertainty in hSSR, the microtremor signals are broken into 120 second time windows, and nFAS and nSSR are calculated for each window. The geometric mean and lognormal standard deviation are computed from all time windows. Given that multiple reference sites were used for all temporary sites, the geometric mean hSSR for the target site, i, is calculated as:

$$\overline{hSSR}_{i/r} = \exp\left[\frac{1}{N_{ref}}\sum_{j=1}^{N_{ref}} \log_e(hSSR_{i/j,r})\right] \quad (6)$$

Where N_{ref} is the total number of reference station measurements for site i. The nine SMS in the Lower Hutt basin discussed in Section 2, at which eSSR relative to a rock site has been calculated from earthquake observations, are used as the permanent basin reference sites, j, to estimate the hSSR at all the temporary target basin sites, i.

In this study, as in de la Torre et al. (2023), the rock station POTS, which is located on the toe of the Wellington hills just outside the sedimentary basin, was used as the reference station, r, to calculate eSSR and hSSR. Further details about this station and why it was chosen as a reference site for the region are provided in de la Torre et al. (2023).

5 VARIABILITY OF MICROTREMOR DATA FROM DIFFERENT DEPLOYMENTS

As discussed in Section 2, seismometers were deployed in groups of four reference basin stations (i.e., the SMS) simultaneously for approximately four hours. For most groups, two separate deployments, on separate days, were required to complete measurements at all the nearby temporary grid sites. This allows for comparison of co-located microtremor measurement amplitudes between different days.

Fig. 2 plots the nFAS and mHVSR amplitudes for a site pair, PGMS and PVCS, at which synchronized microtremor data were collected on two different days (2023-01-17 and 2023-01-18). The top panels plot the horizontal FAS, the middle panels the vertical FAS, and the bottom panels the mHVSR. From the FAS it is clear that higher amplitudes were recorded on 2023-01-18 at both sites in both components. This suggests that environmental factors on this day influenced the Fourier amplitudes at two different sites in a similar manner across the frequency range. The difference between the two days is most pronounced for $f < 1.5$ Hz, and little influence is observed for $f > 2$ Hz.

Interestingly, both the vertical and horizontal components of motion on a given day are influenced similarly by the environmental factors. Therefore, as shown in bottom panels of Fig. 2, the difference in mHVSR between days is less than the difference in FAS, albeit some differences are observed around the peaks.

The ratio of microtremor data between the two sites in Fig. 2 was also calculated, and is plotted in Fig. 3. This confirms that both sites are influenced similarly by the environmental factors on each day, hence, the nSSR is more stable between days than the FAS. Fig. 3 also includes the earthquake eSSR between the two sites. This shows that the earthquake site response is similar between these two nearby sites, especially for $f < 2$ Hz. The nSSR also resembles the eSSR for this site pair, suggesting that the hSSR method should work well between PGMS and PVCS.

It is known that environmental factors, such as wind, wave action, anthropogenic noise, and other unexplained phenomena can influence microtremor measurements (e.g., Bormann and Wielandt, 2013). The fact that these factors influence two nearby sites in a similar manner is important for the application of the hSSR method and is consistent with inherent assumption of the method which utilizes synchronized data between the reference basin site and the target basin site.

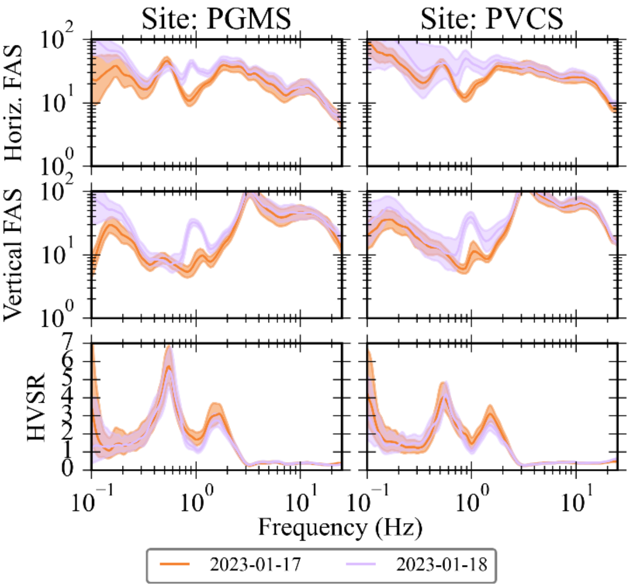

Fig. 2. Mircrotremor horizontal and vertical FAS, and mHVSR for two sites: PGMS (left) and PVCS (right). Data for two days are presented. For a given day, the data from the two sites is synchronized.

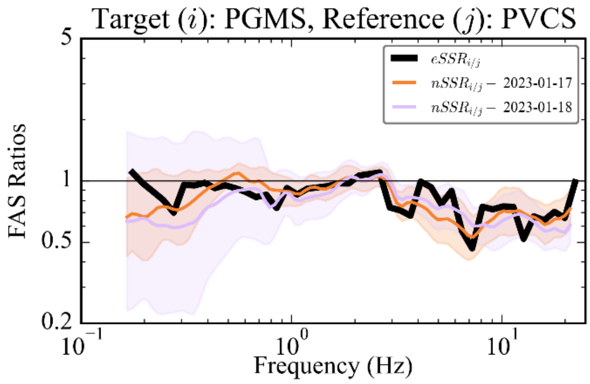

Fig. 3. FAS ratios of ambient noise (nSSR) and earthquakes (eSSR) between two basin sites using PGMS as the target site (i: the numerator) and PVCS as the reference site (j: the denominator).

6 VALIDATION USING THE REFERENCE SMS

A rigorous validation of the method is performed by applying it only to the data recorded at SMS first. Again, for a given group of four reference sites, data was generally collected on more than one day. This allows for comparison of the performance of the hSSR method when synchronized and unsynchronized data are used between the reference basin site and the target basin site (in this case two SMS). The predicted hSSR relative to rock, using a given site pair, can then be compared to the observed eSSR from past earthquakes.

For two example sites, PVCS and LHES, the predicted hSSR are compared to the observed eSSR, relative to the rock site POTS, using both synchronized data (left panels) and unsynchronized data (right panels). The average hSSR, using synchronized data, predicts well the observed eSSR for both sites, especially for f < 5 Hz. At the lower frequencies, all the reference sites (i.e., the individual grey lines) perform relatively well, especially for PVCS. This suggests that the method works well for the group of sites closest to the harbor waterfront which are used as reference to PVCS (i.e. PGMS, SEVS, LRSS).

In Fig. 4, the method is also tested using unsynchronized data for the same two sites. Importantly, for a given target site, the unsynchronized data used here is taken from the same reference sites as the synchronized data, albeit from different days. It is clear that when unsynchronized data is used, significant bias can be introduced at low frequencies. This is consistent with the previous section, which discussed that the environmental factors on a given day may significantly influence the microtremor FAS at sites within the basin, and in a similar way for nearby sites on a given day.

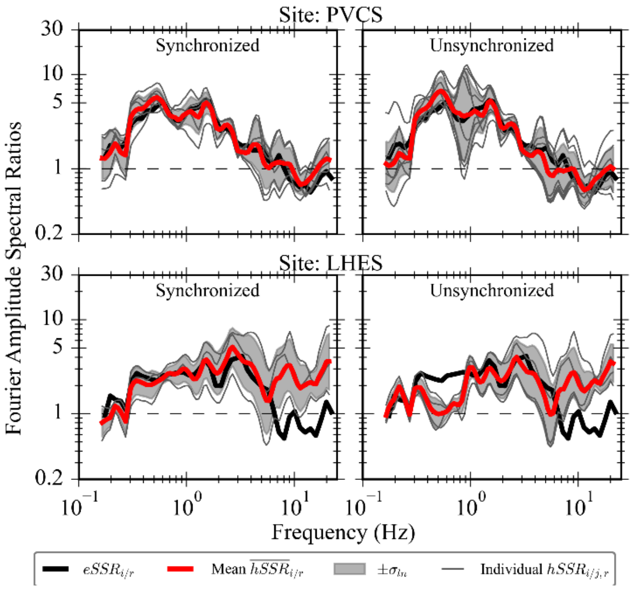

Fig. 4. Predicted hSSR and observed eSSR for two sites: PVCS (top) and LHES (bottom). Results from synchronized (left) and unsynchronized (right) data are compared. Each grey line corresponds to an individual reference site *j*.

The method was applied to all nine reference SMS in the basin. Fig. 5 compares the predicted hSSR and the observed eSSR for all sites, using only the synchronized data. Both the mean for each site and individual $hSSR_{i/j,r}$ for all target site and reference site pairs are provided in the figure. Again, the method performs well, on average, for the majority of sites. It works especially well for the deeper site in the lower half of the basin. There is one outlier, TAIS, at which the method does not work well for most frequencies, and therefore it does not make a good reference site for the nearby SMS (NBSS, LNBS, SOCS). TAIS generally has a lower full site response and is the site furthest up the valley. NBSS is inside a side sub-basin at which very strong site response has been observed. As can be inferred from Fig. 1, the basin geometry (i.e., width and depth) at TAIS and NBSS is different than the rest of the sites.

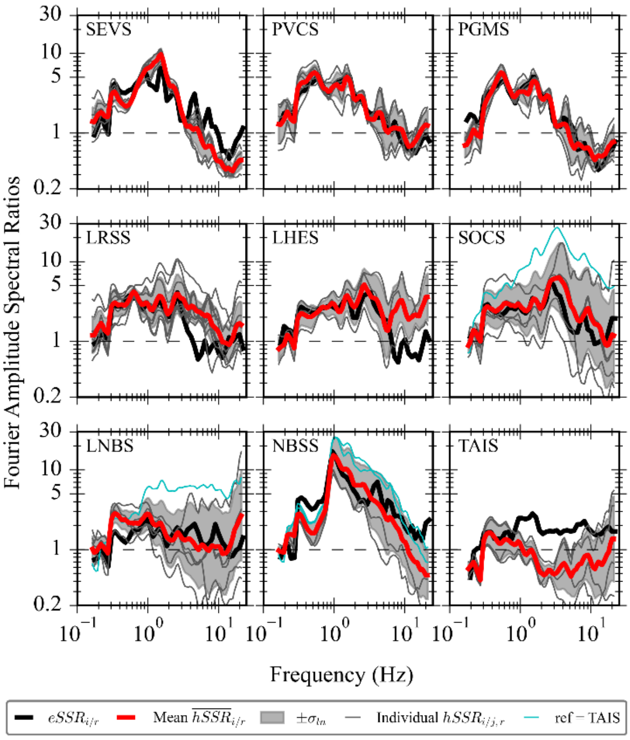

Fig. 5. Validation of predicted hSSR with observed eSSR for all SMS used as reference basin sites. All results are for synchronized data. Each grey line corresponds to an individual reference site *j*. Subplots are ordered from top left to bottom right in increasing distance from the harbor waterfront.

7 APPLICATION TO ALL TEMPORARY MEASUREMENTS IN THE BASIN

After validating the method in the Lower Hutt region, the hSSR method was applied to all temporary target sites at which no earthquake observations exist. All the synchronized data collected over the five days was used, generally corresponding to four reference basin SMS sites for every temporary target site. The mean hSSR for all these locations are plotted versus frequency in Fig. 6. Sites are subdivided into four categories: Lower basin, upper basin, basin-edge west, and basin-edge east. The lines are color-coded by $T_{0,mHVSR}$ for each location. Sites to the NE of SOCS and LNBS are considered upper basin sites, and sites within 300 m of the adjacent hillsides are considered basin-edge.

Fig. 6 shows that the deeper sites in the lower basin generally have a higher site response at lower frequencies. On the contrary, the upper basin sites generally have lower predicted site response at lower frequencies, that increases for $f > 10$ Hz. The basin-edge sites on the western side of the basin along the Wellington fault (see Fig. 1) generally have the lowest site response. Given the relatively low T_0 estimates of these sites, it is believed that these sites are still on the complex step-like geometry near the surface trace of the fault, as discussed in Section 3.

In Fig. 7, the mean predicted hSSR amplitude at a frequency of $f=1$ Hz is plotted versus $T_{0,mHVSR}$ and the depth to bedrock from the 3D velocity model ($Z_{bedrock,VM}$) for all temporary target sites. A moderate positive correlation with $T_{0,mHVSR}$ exists, however the correlation with $Z_{bedrock,VM}$ is weak. This may suggest inaccuracies in the 3D velocity model for certain sub-regions within the basin.

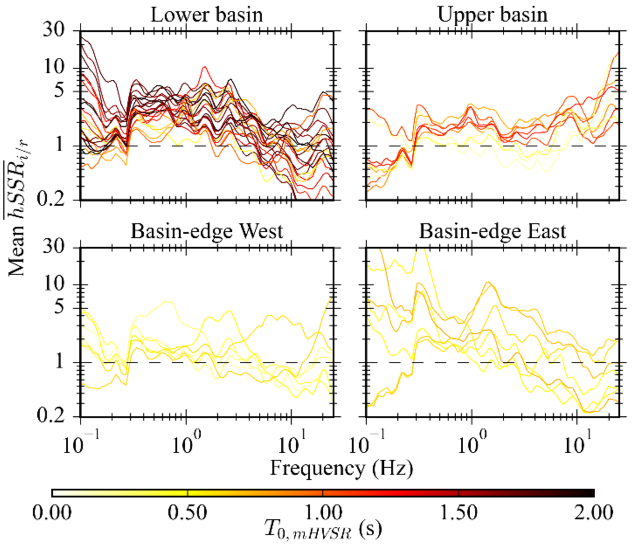

Fig. 6. Predicted hSSR at all temporary grid measurements throughout the basin. Sites are subdivided into four groups: lower basin, upper basin, basin-edge west, and basin edge east.

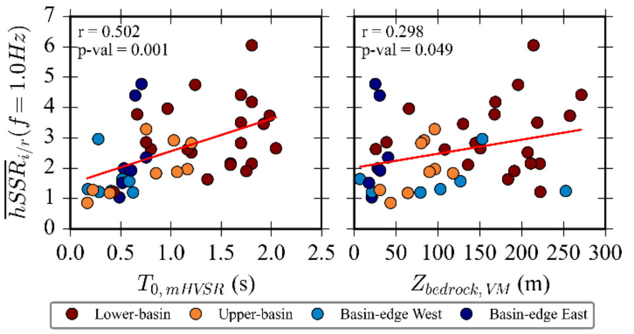

Fig. 7. Predicted hSSR for f = *1.0* Hz at all temporary grid measurements versus $T_{0,mHVSR}$ (left) and $Z_{bedrock,VM}$ (right). Results are color-coded by four geographic categories: lower basin, upper basin, basin-edge west, and basin-edge east sites.

7.1 Preliminary efforts to spatially interpolate the observations and predictions

The mean predicted hSSR amplitudes, at a frequency of $f=1$ Hz, for all sites are plotted spatially in Fig. 8, where site markers are color-coded by the hSSR amplitude. Similar trends discussed in the previous sub-section are observed here, with the deeper basin sites near the harbor having the largest site response at $f=1$

Hz. The SMS NBSS, to the NE of the basin (see Fig. 1) is an outlier with exceptionally high site response at 1 Hz.

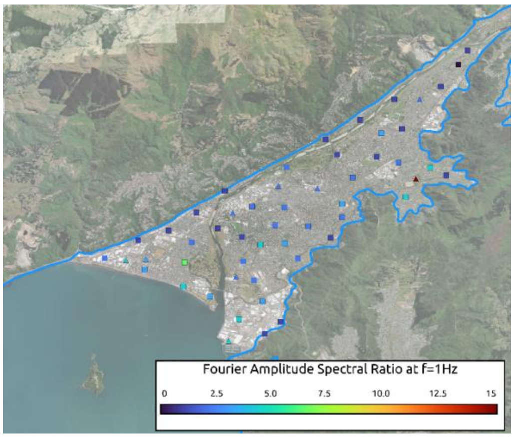

Fig. 8. Map of Fourier amplitude spectral ratios from both observed eSSR (triangles) and predicted hSSR (squares), for $f = 1$ Hz.

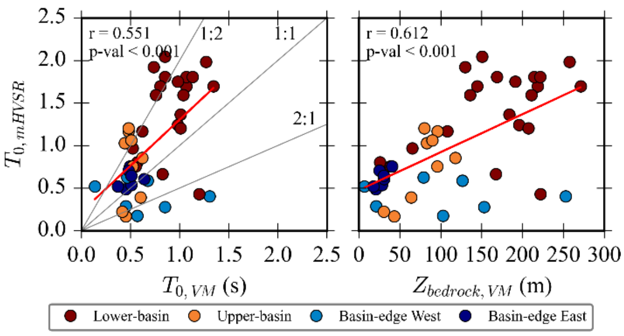

Fig. 9. Comparison of T_0 estimates from mHVSR to T_0 and $Z_{bedrock}$ from the 3D velocity model (VM).

Ongoing work is investigating interpolating between these estimates using Bayesian regression kriging. This approach would utilize some background model(s), such as T_0, $Z_{bedrock}$, or surface roughness to inform the interpolation based on correlations between the predicted site response and these parameters (e.g., Fig. 7). In Fig. 9, the T_0 estimates from mHVSR are compared against T_0 and $Z_{bedrock}$ from the 3D velocity model to superficially scrutinize the accuracy of the 3D VM. While these estimates from the VM in Fig. 9 were extracted at the location of microtremor measurements, these parameters exist across the entire basin. The parameters from the VM are highly correlated to $T_{0,mHVSR}$ estimates, however, there is some bias in the T_0 estimates with many estimates from the VM being 1.5 to 2 times higher than those from mHVSR. This suggests that either the V_S is generally too high or the depth to bedrock is generally too low, however, we believe the depth to bedrock is better constrained.

8 CONCLUSIONS

This study applied the hybrid spectral ratio (hSSR) method, for direct prediction of site response at relatively high spatial resolutions, to a dataset in Lower Hutt, New Zealand. The main conclusions can be summarized as follows:

- Validating the hSSR method using observed earthquake spectral ratios at SMS shows that the method works well in this region, especially for the deeper basin sites at f < 5 Hz.
- Using unsynchronized data can introduce significant bias and uncertainty because of how environmental factors can influence microtremor measurements. This influence is generally similar for nearby basin sites, and for vertical and horizontal components of motion.
- The predicted and observed site response can be significant, especially for basin sites in the lower half of the valley and for f < 3 Hz.

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