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Development of a Waikato Basin T_0 and depth model by the H/V spectral ratio method

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ABSTRACT

This paper presents the development of a preliminary model of the fundamental site period (T_0) across the Waikato Basin using the Horizontal-to-vertical (H/V) spectral ratio technique. We measured the ambient vibration of the ground at over 100 sites across the Waikato Basin, and produced a T_0 map by spatially interpolating T_0 obtained by the H/V spectral ratio technique. The measured site periods were over 5 seconds near Te Rapa and Gordonton, suggesting a deep sedimentary basin. This finding is also consistent with previous studies. We also found that most parts of the Waikato Basin, except very near the basin edge, have fundamental site periods longer than 0.6s, which means they should be categorised as site class D at a minimum, according to NZS1170.5: 2004. More site-specific assessments of shear wave velocity profiles will be able to identify site class E locations. Using the depths to the greywacke basement obtained from the existing petroleum logs in the region, we established a fundamental site frequency-depth correlation.

1 INTRODUCTION

It is well-known that the dynamic response of a soft sedimentary basin amplifies ground motions and prolongs the duration of shaking (Borcherdt, 1970; Kramer, 1996). Therefore, to accurately characterise seismic hazards, we have to understand the dynamic characteristics of sedimentary basins in regions of interest. For example, the fundamental site period (T_0) is a key parameter used to define site subsoil class within the New Zealand seismic design standard (*NZS 1170.5:2004 Structural design actions - Part 5: Earthquake actions - New Zealand*). V_{s30} , the weighted harmonic mean shear wave velocity of the upper 30 metres, is another key parameter to quantify the seismic hazard at a given site (Bradley, 2013; Campbell and

Bozorgnia, 2014). In order to undertake site-specific ground motion analysis or physics-based ground motion simulation, the seismic velocity profile must be fully characterised (Eberhart-Phillips *et al.*, 2010; Graves and Pitarka, 2010).

Despite its relatively low regional seismicity, the impact of a future large earthquake in the Waikato region could be significant, considering the region has a population of 460,000, the fourth largest regional economy in New Zealand (Stats NZ, 2017), and a number of critical infrastructure systems, such as the Waikato expressway, high-pressure gas pipes, and high-voltage electricity transmission lines (New Zealand Lifelines Council, 2017). The surficial geology of Waikato Basin is often characterised by soft, challenging soils, which are known to cause adverse effects in the case of larger magnitude earthquakes (Kramer, 1996; Edbrooke, 2005) but current knowledge on the dynamic response characteristics of Waikato soils is quite limited.

We are currently carrying out a series of geophysical tests to improve our understanding of the dynamic properties of the Waikato Basin and the soils within, as part of the ongoing nation-wide collaborative effort to quantify the site dynamic characteristics of New Zealand basins and urban areas. In this paper, we present the preliminary model for the variation in fundamental site period and depth across the Waikato Basin, developed using the horizontal-to-vertical (H/V) spectral ratio method (Nakamura, 1989) and measured ambient vibrations at the ground surface.

2 GEOLOGIC SETTING

In general, the geology of the Waikato Basin is dominated by thick Quaternary sediments and volcanic ash (Tauranga Group), overlying Oligocene-Miocene sedimentary rock (Waitemata and Te Kuiti Group) and greywacke basement. In the 1960's and 1970's, nine petroleum exploration boreholes were drilled in the Waikato Basin, which are the main source of information about the stratigraphy of the basin (Edbrooke *et al.*, 2009). Figure 1 shows the locations of these boreholes, along with the locations of the H/V test sites. The stratigraphy found in the petroleum boreholes suggests that the Te Kuiti and Waitemata Group rocks are thickest in the west and thin eastwards, which is primarily attributed to the pre-Tauranga Group erosion. Edbrooke *et al.* (2009) summarised the stratigraphy found in the petroleum boreholes, which is reproduced in Table 1.

Table 1: Thickness and depths from the ground surface to the base of stratigraphic groups found in Waikato Basin petroleum boreholes, modified from Edbrooke et al., (2009). NP stands for 'not present'.

Name	Tauranga Group Thickness, H_{TG} (m)	Waitemata Group Thickness, H_{WG} (m)	Te Kuiti Group Thickness, H_{TKG} (m)	Total depth to basement, H_T (m)	H_{TG}/H_T
Puketaha-1	439	NP	NP	439	1.0
Te Rapa-1	610	829	210	1649	0.37
Waikato-1	485	510	30	1025	0.47
Waikato-2	453	437	125	1015	0.45
Waikato-3	200	104	NP	304	0.66
Waikato-4	518	NP	42	560	0.93
Waikato-5	265	512	228	1005	0.26

The basin is bound by the Waipa and Taupiri faults to the West. Previous studies, including the gravity anomaly data and exploration boreholes, suggested the presence of a deep sedimentary basin at the downthrown side of the faults, northwest of Hamilton along a line that connects Whatawhata and Gordonton (Edbrooke *et al.*, 2009). The borehole logs showed that the basement rock is at least 1.6km deep near Te Rapa.

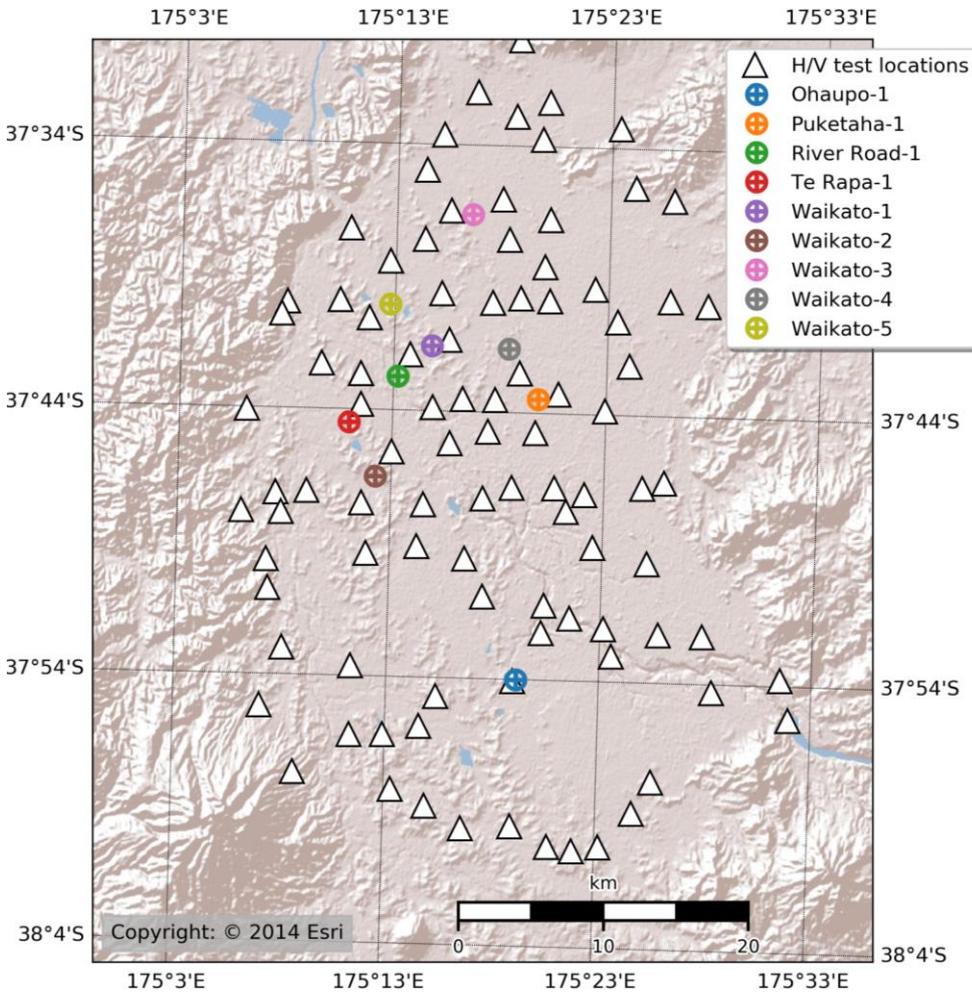


Figure 1: Shaded relief map showing the extent of the Waikato basin. Sun cross symbols show the locations of the petroleum exploration boreholes and the H/V test sites are marked with triangles.

3 METHODOLOGY

1.1 Horizontal-to-vertical (H/V) spectral ratio

The peak frequency from the H/V spectral ratios, the ratios of the horizontal-to-vertical Fourier amplitude spectra of ambient seismic noise, is known to be generally consistent with the fundamental frequency (f_0) of the 1D transfer function of the site (Nakamura, 1989; Sánchez-Sesma *et al.*, 2011).

We collected the ambient vibration records using 3-component broadband seismometers (Nanometrics Trillium Compacts, 20 second period). Each seismometer was placed in a hole approximately 10-15 centimetres deep and oriented towards the magnetic north. Soil was then tightly compacted around the seismometer to ensure a good coupling of the seismometer with the surrounding ground. The ambient vibration testing took place between November 2018 and February 2019. We deployed the seismometers at over 100 sites across the Waikato basin as shown in Figure 1. At each site, we recorded the ambient vibration for approximately 60 minutes. A sampling rate of 100Hz was used in all cases.

The ambient vibration data were processed using the software Geopsy (www.geopsy.org). Recorded motions were divided into multiple time windows of 180 seconds with a 5% cosine taper. Time windows including large transient spikes and time windows producing obviously erroneous spectral ratios were rejected in the processing stage. The geometric mean horizontal Fourier amplitude spectra were used to compute the H/V spectral ratios, and each amplitude spectrum was smoothed by a Konno-Ohmachi window (Konno and Ohmachi, 1998) with a smoothing constant $b = 40$.

2 SITE PERIODS IN THE WAIKATO BASIN

Figure 2 shows typical H/V spectral ratios from sites within the Waikato Basin. The majority of sites show a very clear fundamental mode peak with a large amplitude, indicative of a large impedance contrast. Also, in most cases, the lowest frequency (longest period) peak in the H/V ratio showed the largest amplitude. The peaks of the lowest frequency in the H/V spectral ratios likely correspond to, in most cases, fundamental mode vibration of the entire soil profile down to the basement rock (greywacke), and this is the focus of our study in this paper.

It is possible that, at some sites, a shallower impedance contrast dominates the lowest frequency peak (Toshinawa *et al.*, 1997; Wotherspoon *et al.*, 2015). We plan to characterise the V_s of soils and sedimentary rocks of the Waikato Basin using the multichannel analyses of surface waves (MASW) and the microtremor array method (MAM), which is expected to help us better interpret the H/V spectral ratios of the Waikato Basin in the future. H/V spectral ratios at some sites can also feature multiple H/V peaks, and there are a few possible situations in the Waikato area that could cause such multiple peaks in the H/V ratio. This includes the impedance contrast between the Tauranga Group and the Waitemata Group or the impedance contrast between the Pirongia volcanic formation and the younger quaternary sediments. Figure 2 shows examples of second peaks at higher frequencies with less pronounced amplitudes, which could be due to the response of shallower soil layers. Towards the southern end of the basin near Te Awamutu, a few sites even showed three peaks in their H/V ratios, which is indicative of a complex layering of sedimentary soils and the volcanic formations.

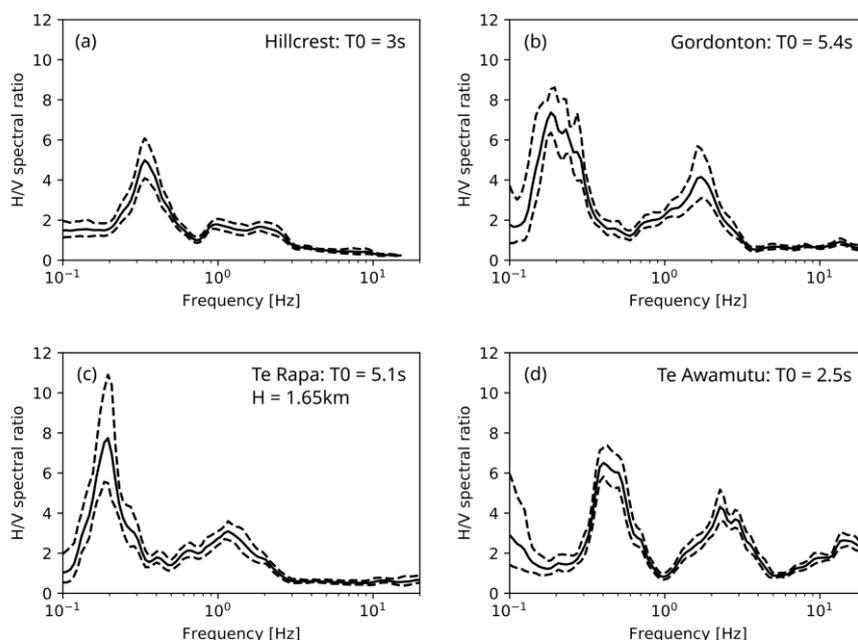


Figure 2: Examples of H/V spectral ratios obtained in the Waikato Basin. Nearly all sites show a clear fundamental mode of vibration with large amplitude ratios.

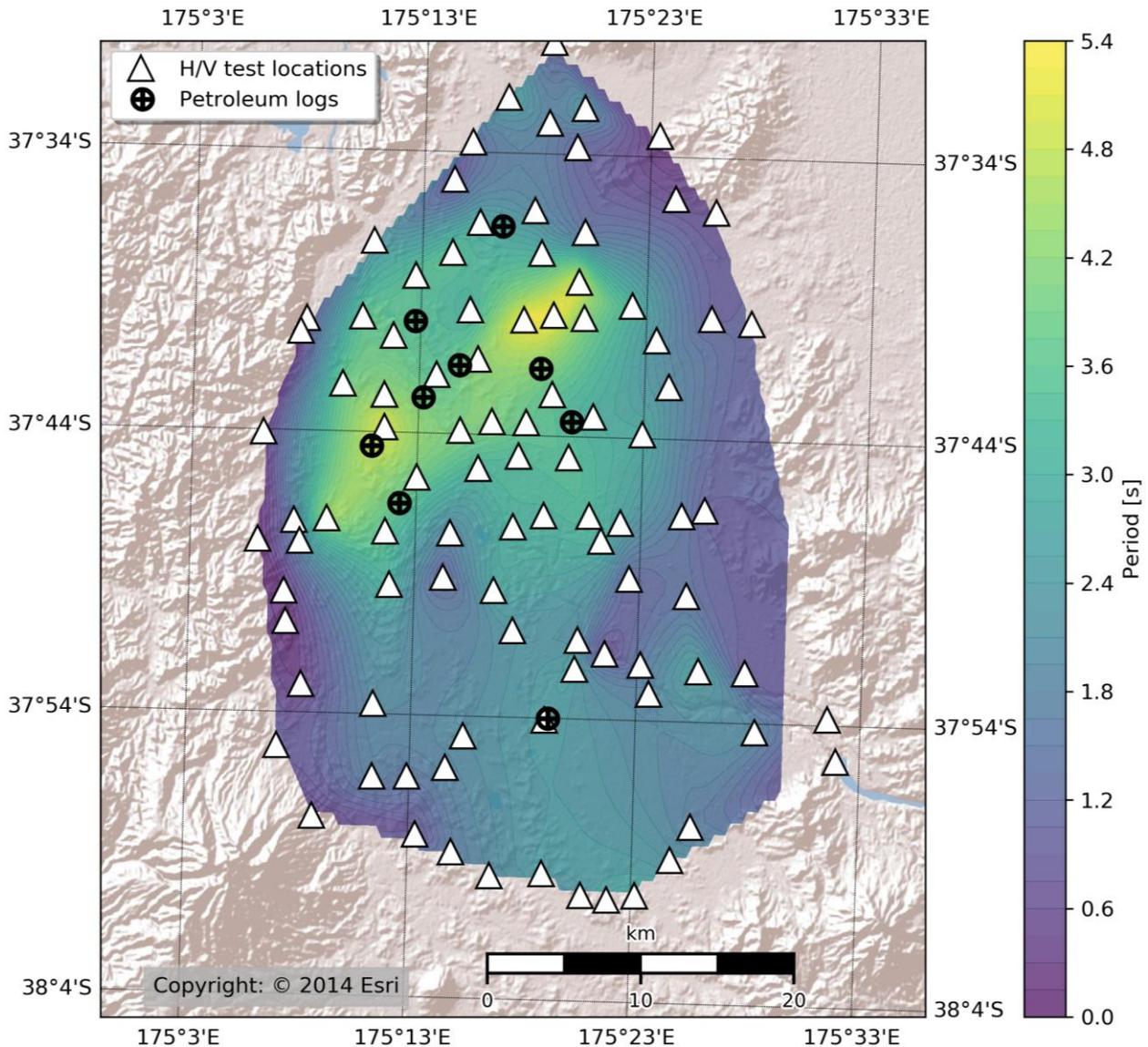


Figure 3: Interpolated map of T_0 across the Waikato basin. Also shown are the H/V test sites and the locations of petroleum borehole logs.

To create a map of the fundamental period across the Waikato Basin, we spatially interpolated the fundamental period of tested sites using the Natural Neighbor algorithm (Sibson, 1981). Figure 3 shows the fundamental site period map of the Waikato Basin, along with locations of the H/V test sites. Also shown in the same figure are the locations of existing petroleum boreholes at which the depths to the basement rock are known. Figure 3 shows that the fundamental site period can be over five seconds in some locations, and the longest site periods are observed from the west through to the north of Hamilton, almost along a linear trend that goes through Whatawhata, Te Rapa, Rototuna, and Gordonton; we also found that the site periods change rapidly near the areas of longest site periods. The shape of the contour of T_0 is consistent with the gravity anomaly of the region (Frogtech, 2011), and the borehole log Te Rapa-1 showed that the greywacke basement was encountered approximately at 1.6km. Figure 3 suggests that most places within the Waikato basin should be categorised as the site class D, according to NZS1170.5: 2004, except where it's very close to the basin edge.

3 FUNDAMENTAL SITE FREQUENCY-BASIN DEPTH CORRELATION

Previous studies showed that the relationship between fundamental frequency (f_0) of a soil layer and its thickness (H) can be defined by a power-law equation (Ibs-von Seht and Wohlenberg, 1999; Parolai *et al.*, 2002):

$$H = af_0^b \quad (1)$$

where a and b are coefficients that can be defined for different deposits and locations. Using the depth to the basement logged at the petroleum boreholes and the interpolated site frequency, we carried out a regression analysis to establish a correlation between the basin depth, H , and the fundamental site frequency, f_0 . Figure 4 shows the observed depth-interpolated f_0 pairs, along with a power law model obtained by the regression analysis represented by:

$$H = 101.6f_0^{-1.565} \quad (2)$$

We also compared our data with two previous studies (Ibs-von Seht and Wohlenberg, 1999; Parolai *et al.*, 2002). We found that both of these models fit our data reasonably well, but the Parolai *et al.* (2002) model was much closer to the model we obtained. Large uncertainties should be expected from a simple model of this form, as the model simply ignores the local variability of the shear wave velocity and implicitly assumes that the V_s of the soil within the basin can be defined by a unique function.

In Figure 4, equation (2) clearly over-predicted the depths at boreholes Puketaha-1, Waikato-3, and Waikato-4. The ratio H_{TG}/H_T in Table 1 suggests that the Tauranga Group soils dominate the geology of these sites, which means that the actual average V_s are likely lower at these sites compared with other locations. In other sites where the model under-predicted the depths, the thickness of Oligocene-Miocene sedimentary rocks is considerable. Such variability in the basin geology will likely cause the variability of V_s , which contributes to the prediction uncertainty.

We plan to improve our model in the future to account for the spatial variability of the V_s . Nevertheless, we found that the predictions are generally within a range of 0.7 to 1.5 times the observed depths. However, because all the petroleum boreholes showed the basement depths greater than 250m, the current model is not well constrained near the edge of the basin where fundamental frequencies are greater than 1Hz (or periods shorter than 1s).

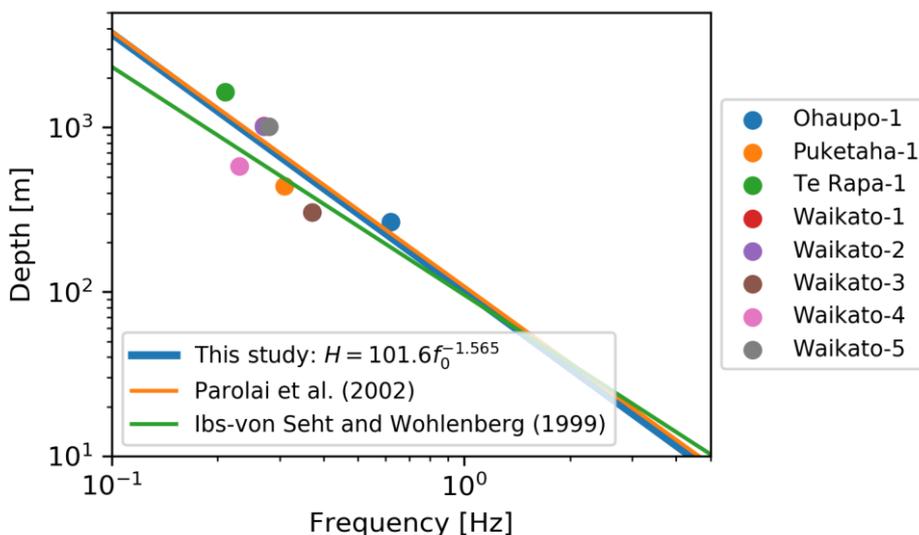


Figure 4: H - f_0 model developed using the measured f_0 and H .

4 CONCLUSIONS

We developed a fundamental site period map of the Waikato basin, which was derived from ambient-vibration H/V spectral ratios obtained from over 100 sites across the Waikato basin.

One of the petroleum logs (Te Rapa-1) showed that the depth to basement is nearly 1.6km near Te Rapa. The measured site periods were over 5 seconds near Te Rapa and Gordonton. It is expected that those are the locations where the basement rock is the deepest; we also found that the site periods change rapidly near the areas of longest site periods.

We found that most of the places in the Waikato Basin, except where it's very near the basin edge, have fundamental site periods longer than 0.6s, which means they should be categorised as the site class D at a minimum, according to the NZS1170.5: 2004. More site-specific assessments of shear wave velocity profiles will be able to identify site class E locations.

Using the measured site frequencies and the depths to the basement observed in previous studies, we developed an empirical model that estimates the bedrock depth using the obtained fundamental site frequency. Uncertainty is expected as this model does not account for the spatial variability of soil velocities, and the predictions are generally within a range of 0.7 to 1.5 times the observed depths. However, it should be noted that the current model is not well constrained at locations where depths are less than 250m.

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