Earthquake Commission Report

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‘Rapid’ geophysical characterisation of New Zealand sedimentary basins using the horizontal-to-vertical spectral ratio method

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Summary

Earthquakes in New Zealand and internationally have demonstrated the influence of sedimentary basins on site amplification. However, apart from a handful of detailed site characterisation studies, few basins in New Zealand have been characterised to a level that basin effects can start to be quantified. This report presents a 'rapid' geophysical characterisation approach that can allow for faster dissemination of basin characteristics that can feed into research and practice while more refined models are developed. This method is based on representative deep shear wave velocity profiles from surface wave testing and estimates of fundamental site period across the basin based on horizontal-to-vertical spectral ratio testing. Using the relationship between the shear wave velocity profile and site period, basin depths can be estimated at each site period testing location, informing the development of basin models.

As part of this project, new regional geophysical site investigation studies were undertaken in Waikato, Hauraki Plains and Hawke's Bay. Deep shear wave velocity profiles and site period estimates across these regions have improved understanding of the properties of regional soil deposits and the regional variability in dynamic site characteristics. In Waikato fundamental site periods in excess of 5 seconds were recorded, while in the Hauraki Plains, site periods were greater than 6 seconds in some areas, suggesting deep basins in both regions. Fundamental site period estimates in the Napier area were less than 2 seconds in most locations, reducing closer to the surrounding hills and Bluff Hill. South of Napier and across much of the remainder of the Heretaunga Plains, some of the H/V peaks were likely representative of a shallower impedance contrast, and not the overall soil profile to bedrock. Variation in depth to bedrock in this area aligned well with the surrounding topography.

New deep shear wave velocity profiles from south of Napier were used in combination with the site period estimates in the Napier area to estimate the basin depth using the 'rapid' method. This was able to provide insight into the structure and shear wave velocity of the deposits in the basin under Napier. Site period estimates from Waikato and the Hauraki Plains were used in combination with new deep shear wave velocity profiles from Waikato to estimate the basin depth in these regions. These were compared against models constrained using regional topographic data. There were clear differences between the two model types in some areas, with the 'rapid' method likely providing a better representation of the basin structure, based on comparisons with other investigation data, and provide additional insight into the basin structures. The 'rapid' method was applied to existing site period estimates and deep shear wave velocity profiles from Canterbury, where a high resolution basin model already exists that has been constrained by a number of datasets. The depth estimates from both models were in good agreement, demonstrating the usefulness of the method in providing initial information on basin structure that can inform regional site classification for seismic design, regional near surface shear wave velocity models, and the development of velocity models for physics-based ground motion simulation.

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1 Introduction

This report summarises the development and application of a methodology to provide ‘rapid’ geophysical characterisation of New Zealand sedimentary basins using the horizontal-to-vertical spectral ratio method (H/V method) and deep shear wave velocity (V_S) profiles. Detailed characterisation of basin structures, although the final goal, is a long process, meaning that advancement of the understanding of potential ground motion amplification can take many years. The ‘rapid’ characterisation approach allows for faster dissemination that can feed into practice while more refined models are developed. This project has leveraged off a range of studies that are currently underway or recently completed to inform the development of the ‘rapid’ basin site characterisation metrics.

There is currently little geophysical investigation data, particularly fundamental site period data, across most basins in New Zealand. More focus has been given to regions affected by recent earthquakes, such as Canterbury and Wellington. Given the paucity of dynamic site characterisation data across New Zealand, this research will greatly enhance the understanding of basin structures and the characteristics of regional deposits. It will improve regional site classification for seismic design, regional near surface V_S models, and the development of velocity models for physics-based ground motion simulation.

The initial step in this research was the review of existing site investigation data that could inform basin dynamic site characteristics across New Zealand. The field investigation methodology for the collation of data using the H/V method and the development of deep V_S profiles is then discussed. Using this approach, the outputs from field investigations in three new regions are presented. The ‘rapid’ basin model methodology is summarised along with another simplified method based on geologic and topographic data within and surrounding each basin. The final section presents each basin model, compares them against existing models where available and discusses these comparisons.

2 Existing Basin Characterisation across New Zealand

The first step in this research was a review of existing site investigation data related to sedimentary basins across New Zealand, with a focus on the dynamic site characteristics. Coarse scale national maps of basin depth have been developed in previous work (Perrin, unpublished maps); however, although some geophysical data has been used in their compilation, these have largely been constrained with geologic data (Kaiser et al. 2017). We have defined the quality of basin characterisation based on the types of data sources used in development, the method of interpretation of data sources and the spatial distribution of data sources in relation to basin extent. As the focus is the influence of these basins on earthquake shaking, the data sources of interest are those that constrain the dynamic site characteristics, such as shear wave velocity of regional deposits and the dynamic characteristics of the overall soil profile.

The following classification system is used to define the quality of data available in each basin:

- Poor – Little site period or V_S data
- Average – Site period data across region
- Moderate – Site period data across region and shallow V_S data
- Good – Good coverage of site period data across region and deep V_S data

A summary of the basin characterisation details for the selected regions is provide in Table 1. Within this table the abbreviations H/V is used for H/V spectral ratio testing, and V_s is used for surface wave and invasive method V_s testing.

Table 1. Summary of level of geophysical characterisation of a selection of New Zealand sedimentary basins for seismic analyses.

Region	Exploration Methods	Geology	Geophysical Studies	Characterisation Level
South Auckland	Surface wave testing, extensive geotechnical, groundwater investigations.	Depth of Quaternary deposits >200 m. Mainly Tauranga Group alluvium with minor tephra and loess.	H/V – Stephenson et al. (1997) V_s and H/V – Dawson et al. (2015)	Poor overall Good in Takanini
Hauraki Plains	Seismic transects and gravity surveys. Extensive groundwater bores.	Maximum depth of Quaternary deposits ~3000 m. Consists largely of Hinuera Formation, alluvial volcaniclastic sediments and unconsolidated swamp, marine and alluvial deposits.		Poor
Hamilton	Gravity mapping, oil exploration boreholes, geotechnical and groundwater boreholes.	Depth of Quaternary deposits ranging from 200 - 700 m. Consists of mostly of Tauranga Group alluvium and the Hinuera Formation comprising of unconsolidated alluvial deposits, pumiceous clays, sands and interbedded peats.		Poor

Table 1 cont.

Region	Exploration Methods	Geology	Geophysical Studies	Characterisation Level
Tauranga	Seismic exploration offshore and surface wave testing. Geotechnical and groundwater boreholes.	Depth of deposits highly variable ranging from 10 m to 300 m. Matua subgroup consist of pumiceous alluvial gravels, sands, mud and thin beds of peat. Holocene deposits overlie Matua subgroup and consist of unconsolidated dune sands and marine muds and gravels.	V_s & H/V – Pearse-Danker & Wotherspoon (2016) H/V – Wotherspoon (unpublished)	Average
Rangitaiki	Gravity and resistivity mapping. Seismic surveys. Surface wave testing. Geotechnical and groundwater boreholes.	Manawahe and Awakaponga Formations occur in northern and southern parts and consist mainly of loose pumiceous sands, minor mud and gravels. Holocene alluvium and swamp deposits consist of poorly sorted gravels, fine sands, silts mud and beds of peat.	V_s & H/V – Beetham et al. (2006)	Poor overall Moderate in Whakatane
Taranaki	Extensive hydrocarbons exploration wells. 2D and 3D seismic surveys. Deep downhole Vs and surface wave testing	Quaternary deposits are <200 m thick and consist of unconsolidated sands, muds with minor gravels and shellbeds of various thicknesses. Holocene deposits consist mainly of volcanic lahars, pyroclastic deposits with tephra and ash, overlying older Quaternary sediments.	V_s – BECA (unpublished) H/V – Wotherspoon (unpublished)	Poor

Table 1 cont.

Region	Exploration Methods	Geology	Geophysical Studies	Characterisation Level
Whanganui Basin	Seismic transects, magnetic and gravity surveys. Extensive hydrocarbon exploration wells.	Deep sequence of up to 4.5 km thick consisting of shallow marine sediments. Tangahoe Formation consists of shallow marine sandy mud, shellbeds and sandstone. Holocene deposits consist of shellbeds, fine sands, gravels and loess with minor volcanic ash.		Poor
Gisborne	Seismic transects and boreholes.	Quaternary deposits up to 300 m thick. Mangatuna Formation consisting of river and estuary derived gravels, sands, silts and mud form the Early Quaternary deposits. Holocene deposits consist of flood plain silts/muds, river gravels and sands.		Poor
Hawke's Bay	Reflection surveys and surface wave testing. Geotechnical and groundwater boreholes.	Thickness of Quaternary sediments are up to 1600 m thick. Kidnappers Group comprises of terrestrial and marginal marine gravels mud, silts fine sands and traces of volcanics. Early Quaternary deposits occur in the southern part of the basin and consist of alluvial and colluvial derived gravels, intertidal sands and muds.	H/V – Hengesh et al. (1998)	Poor

Table 1 cont.

Region	Exploration Methods	Geology	Geophysical Studies	Characterisation Level
Wairarapa	Seismic and gravity surveys, surface wave testing. Geotechnical and groundwater boreholes.	The maximum thickness of the deposits is roughly 400 m. The Early Quaternary Te Muna Formation consists of poorly sorted alluvial gravels, lacustrine silts and silty clays. The Late Quaternary deposits found in the southern and central portion of the basin consist of poorly sorted gravels and fine-grained sands.	V_s – Kaiser & Smith (2005)	Poor
Hutt Valley	Seismic and gravity profiles, surface wave testing. Extensive geotechnical and groundwater boreholes.	Mostly Holocene deposits up to 350 m thick. They consist of alluvial-marginal marine sediments with poorly sorted gravels and fine-grained sands. Shellbeds are found at 100 m depth with thin beds of peat.	Summary – Boon et al. (2011)	Good
Wellington CBD	Seismic and gravity surveys. Surface wave testing and invasive Vs methods. Geotechnical and groundwater boreholes.	Holocene and Pleistocene deposits up to 200 m thick. Engineered fill overlying alluvial, colluvial and marine deposits. Pleistocene alluvial and beach deposits below this.	Summary – Kaiser et al. (2019)	Good

Table 1 cont.

Region	Exploration Methods	Geology	Geophysical Studies	Characterisation Level
Nelson-Tasman	Seismic profiles, surface wave testing. Geotechnical and groundwater boreholes.	Deepest at Moutere Depression at 2500 m. Port Hill Gravel within Nelson City, up to 500 m thick. Holocene deposits of unconsolidated gravels, sands with peat deposits found throughout basin, up to 55 m thick.	V_s & H/V – McMahon (2018)	Poor overall Moderate in Nelson
Wairau Plains	Regional gravity survey. Surface wave testing.	Early Pleistocene deposits are approximately 800 m thick consisting largely of glacial outwash. Holocene sediments up to 50 m thick consist a variety of unconsolidated gravels, sand, silt and clays. Minor peat is also encountered around Blenheim.	H/V – Robertson & Smith (2004), Jeong (unpublished)	Average
Culverden	Gravity survey, surface wave testing.	Maximum depth of Quaternary sediments up to 400 m. Pleistocene deposits consist of alluvial and glacial gravels, sands, silts and loess. Holocene deposits consist of alluvial fans, silts and clays.	H/V – Jeong (unpublished)	Average
Canterbury Plains	Seismic, magnetic and gravity surveys. Surface wave testing and invasive Vs methods. Geotechnical, groundwater and exploration boreholes.	Alternating sequences of gravel and marine sediments that can exceed 2000 m. Late Pleistocene deposits of gravels of varying age and sand. Holocene deposits consist of sands, silts and gravels.	Summary – Lee et al. (2017)	Good

3 Site Investigation Methodology

Geophysical site investigation methods can be used to define the dynamic site characteristics across a region. This research focussed on the use of non-invasive, non-intrusive methods, including surface wave methods and the horizontal-to-vertical spectral ratio method (H/V method).

The H/V method (Nakamura 1989, Field et al. 1990, Field & Jacob 1993, Sánchez-Sesma et al. 2011) was used to estimate the fundamental site period (T_0) at each test location, a characteristic of the dynamic response of the overall soil profile above bedrock. Test locations were dispersed across each basin using a staged field investigation approach. Existing geologic and geotechnical investigation data was used to inform the placement of test locations. The output of this testing was a geospatial collation of point site period measurements, with the variation of site period across the basin providing a first level representation of the basin structure.

Active and passive surface wave methods were used in combination to develop V_S profiles with associated uncertainty at each test location. Testing was undertaken at a single deep location within the basin to provide a representative V_S profile for the basin. There is likely to be variation in the V_S characteristics across each basin, and over time further deep profiles can be developed and assigned to particular areas of the basin. For the purposes of this 'rapid' method, a single profile is used that is deemed representative of the wider basin. These methods require no plant or heavy equipment, meaning that testing can be carried out at a large number of sites in a timely manner and at low cost. The specifics of the methods used in this study are summarised in the following sections.

3.1 H/V Method

To rapidly characterize the fundamental site period (T_0) across each study area, the H/V method on ambient vibration records was used. A well-defined peak in the H/V data can be used to infer (1) the fundamental site period for the entire soil profile down to bedrock (a significant impedance contrast); or (2) the natural period of the soil profile above a shallower impedance contrast.

Ambient vibration records were collected using three-component seismometers (Nanometrics Trillium Compacts 20s) with a flat frequency response between 20 seconds and 100 Hz. Each seismometer was either (1) placed in a hole approximately 10-15 cm deep and then surrounded by tightly compacted soil to provide good coupling with the surrounding ground; or (2) placed on a levelling cradle on a solid surface.

For sites in close vicinity (less than a few hundred metres) to the hills surrounding each basin, 30 minute records were taken at each location. For sites further out than this, recording periods of at least 60 minutes were used. A sampling frequency of 100 Hz was used in all cases.

H/V data were processed using the software Geopsy (Wathelet 2008). Time windows that were overly noisy were removed, with the remaining windows used to develop the spectral average at each location. The geometric mean of the horizontal-component Fourier spectra were used to develop the H/V spectral ratios, and a Konno & Ohmachi (1998) smoothing function with a smoothing constant of b=40 was applied. The H/V spectral ratios from a range of time window lengths were compared during processing to determine the influence of window lengths on the estimated spectral peak(s) and to estimate the uncertainty associated with the spectral peak(s). The data presented in this paper used window lengths between 30 and 180 seconds, with no overlap and a 5% cosine taper.

Peaks identified in the H/V data were assessed for clarity and reliability following the SESAME (2004) guidelines and then related back to the geologic knowledge of the region. At each site, estimates of the mean site period and associated uncertainty will be defined using this approach. Figure 1 provides examples of peaks representative of a deep impedance contrast, a shallow impedance contrast, and multiple impedance contrasts.

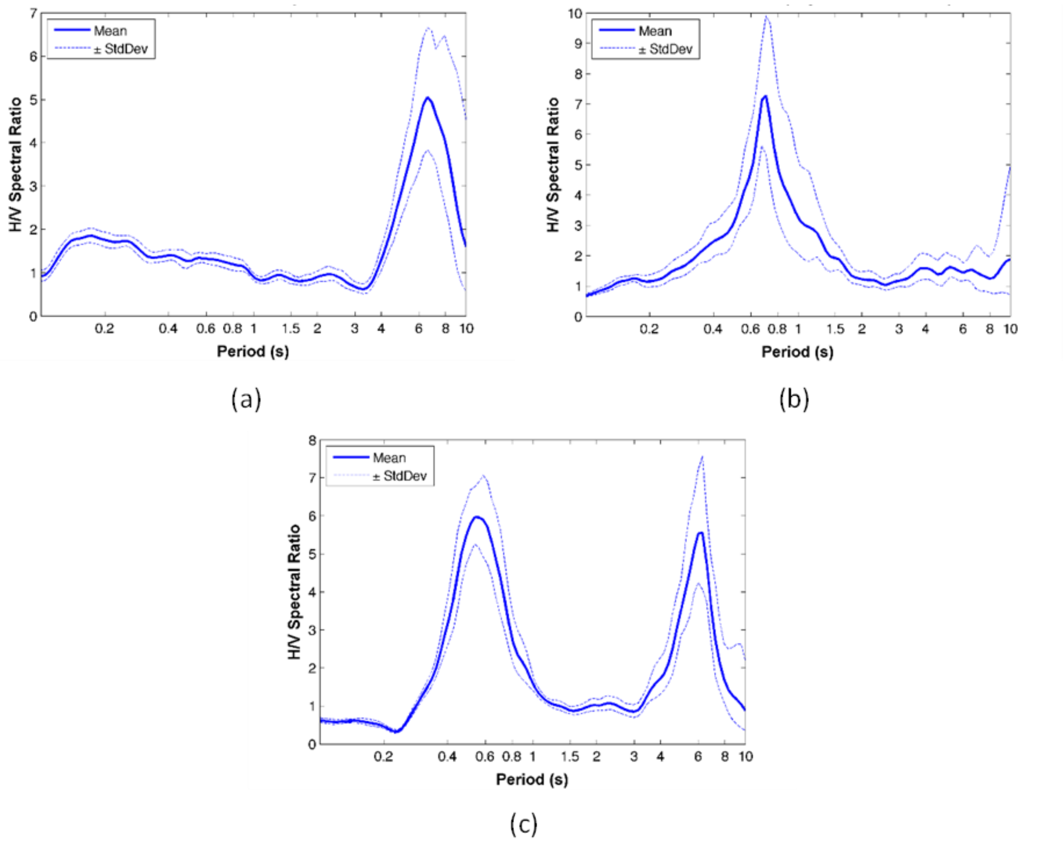

Figure 1. Example H/V data from ambient noise records across Canterbury (a) Single predominant peak corresponding to the fundamental site period above basement rock; (b) Single predominant peak corresponding to period of profile above shallow volcanics; (c) Double peak corresponding to both the fundamental site period and the period of the profile above the shallow Riccarton Gravels (after Wotherspoon et al. 2018).

3.2 Surface Wave Methods

A combination of active-source and passive-source microtremor array measurement (MAM) surface wave methods were used to resolve the V_S and layering for each location where detailed characterisation was required.

3.2.1 Active Source Methods

Active source data was acquired using a sledgehammer source with a steel strike plate with a rubber damping pad to collect Rayleigh wave data. A total of 24 4.5 Hz vertical geophones with 2 m spacing were used to collect Rayleigh wave dispersion data. Four source offsets of 5, 10, 20 and 40 m were used, and at each source offset at least five sledgehammer impacts were recorded and stacked.

The active-source MASW data were processed using the Frequency Domain Beamformer (FDBF) method in combination with the multiple-source offset technique (Zywicki 1999, Cox and Wood 2011). The use of multiple source offsets during data collection and processing allows for quantifying dispersion uncertainty and the identification of near field contamination. The dispersion data from each offset was cleaned and combined to develop a single composite experimental dispersion curve. The data was then divided into frequency bins and the mean phase velocity and standard deviation defined for each bin.

3.2.2 Passive Source Methods

Passive data were collected using eight 3-component broadband seismometers, the same as those used for the H/V method. Seismometers were typically arranged in circular arrays with diameters of 50, 200 and 500 m at each location. The ideal layout at each array consisted of a central location and seven locations spaced evenly around the circumference; however, constraints at some locations required slight modifications to this layout. Larger arrays, either circular or triangular, were used at each location depending on the available space. The field installation was similar to that described in the H/V method section. Ambient noise was recorded for one hour for the 50 m and 200 m arrays, two hours for the 500 m array, and three hours for the larger arrays.

Rayleigh wave dispersion data from the vertical components of the ambient noise recorded from the circular arrays, and in some cases Love wave dispersion data from the horizontal components, were computed using the HRFK method (Capon 1969). For a typical survey the time records for each array were divided into 180 second time windows, resulting in 20 to 40 windows for each array and ensuring a sufficient number of cycles for each frequency. Peak wavenumber pairs were selected at 125 frequency points distributed logarithmically between 0.1 and 20 Hz for each time window, resulting in 20 and 40 phase velocity values for each frequency. A single composite experimental dispersion curve was then developed by combining the individual dispersion curves from each array.

The dispersion curves from each array were then compared to identify and remove significant deviations from the composite trend, such as effective mode data and near-field effects. Dispersion data with wavenumbers outside of the maximum and minimum array resolution limits (Wathelet 2008) were considered less reliable than data within the limits and removed in most cases. Following elimination of poor quality data, the dispersion curves from all arrays were averaged to form a single composite dispersion curve.

3.2.3 Inversion Methodology

The open-source software package Geopsy (Wathelet 2008) was used to perform a multi-mode, joint inversion of the dispersion data for each site. The forward model calculations were originally developed by Thomson (1950) and Haskell (1953) and later modified by Dunkin (1965) and Knopoff (1964). As the surface wave inversion problem is ill-posed and non-unique, hundreds of thousands of possible profiles are considered in each inversion, and any of the models with sufficiently low misfit to the experimental data may be representative of the velocity structure at the site. Rather than providing a single, deterministic V_S profile for each site, the inversions provide a suite of theoretical profiles that fit the experimental data well.

The user defined constraints or layer parameterization for the inversion are velocity (V_S and V_P), depth, Poisson's ratio, density, and the number of layers in the soil profile. The use of a parameterization aids the inversion process by reducing the size of the solution space from which velocity profiles can be generated. As there was no a priori subsurface information to help constrain the inversion process, the layering ratio approach of Cox and Teague (2016) was utilised. This provides a systematic approach for the definition of the number of layers and the depth range of these layers within the parameterization. Multiple layering ratios were used in order to represent the most reasonable models for each site.

For each site, hundreds of thousands of models with corresponding Vs profiles, Rayleigh and Love wave dispersion curves, and ellipticity curves were generated for each layering ratio in an effort to obtain the best dispersion curve fit. Within Geopsy, the misfit or the overall 'closeness' between the experimental and theoretical dispersion curve is computed for each model. In order to obtain the closest fit of the experimental dispersion curve, Dinver attempts to minimize the misfit at each frequency point along the experimental dispersion curve. For each layering ratio at each site, the 1000 lowest misfit or closest fit profiles were extracted and used as a representative sample to generate a characteristic median V_S profile and to represent the uncertainty for each site.

4 Field Characterisation Results

This study had focussed new field characterisation in basins where there is currently little existing geophysical investigation data. The choice of these locations was also guided by the population and economic importance of the regions and the importance of the regional infrastructure (as well as accessibility for testing). The new field characterisation data was from the following regions:

- Hauraki Plains
- Waikato
- Hawke's Bay

The site period data and deep V_S profiles are presented, and their characteristics discussed in relation to the current understanding of the structure of these basins. The site subsoil classification for seismic design as part of NZS1170.5 (2004) is also discussed.

4.1 Hauraki Plains

Site period estimates were collated at 100 sites across the Hauraki Plains. Multiple peaks in the H/V data, indicative of multiple impedance contrasts, were present at a few sites, with the majority having a single peak that likely represents the entire soil profile down to basement rock. The clarity of the peaks in the H/V data varied across the region, which could be due to poor coupling of the sensors during installation, or variability in the strength of the impedance contrast. At all sites the fundamental site period was likely identified.

A map of the fundamental site period estimates across the Hauraki Plains is presented in Figure 2. The majority of the Hauraki Plains, apart from the basin edge region, have fundamental site periods greater than 0.6 seconds, representative of minimum of site class D according to NZS1170.5. Fundamental site periods in excess of 6 seconds were measured at some locations, suggesting a very deep sedimentary basin. The spatial variability of the site period estimates is in line with the presence of a shallower ridge running through the central portion of the plains that is part of the Hauraki Rift half graben structure. This has been identified in previous studies, such as the gravity survey of Hochstein & Nixon (1979). Site periods are shortest along the basin edge where the basin depth is its shallowest, with the next shortest set of site periods in the region along the central ridge structure, with periods between 0.8 and 2.0 seconds. Between the basin edges and the central ridge the basin deepens significantly, with some suggestion that the depth in these areas increases moving from south to north (from right to left in Figure 2). The results of this are discussed in more detail in Rana (2019).

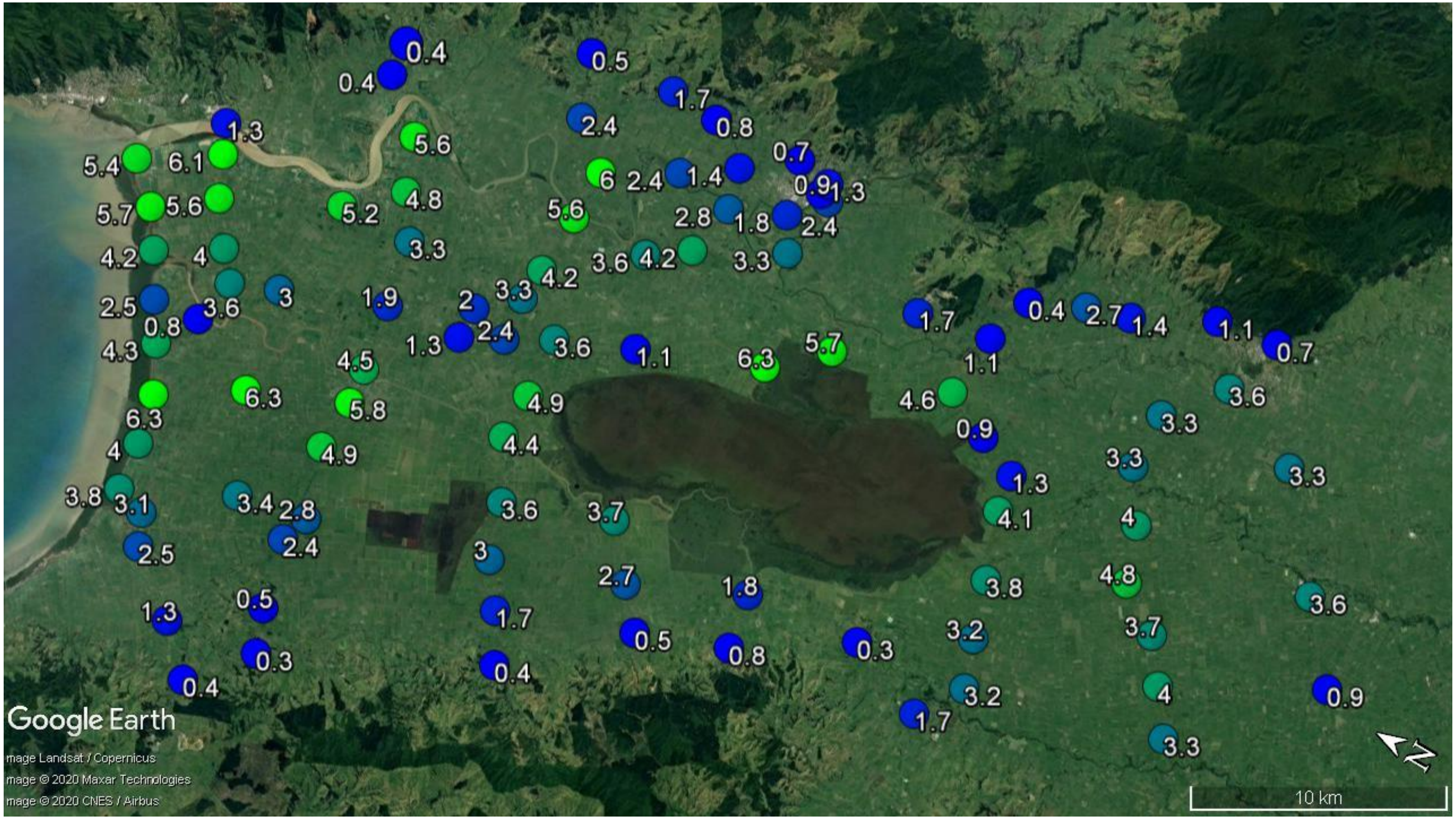

Figure 2. Fundamental site period estimates across the Hauraki Plains region.

4.2 Waikato

Site period estimates were collated at over 100 sites across the Waikato Basin. The majority of sites show a very clear fundamental mode peak in the H/V data with a large amplitude, indicative of a significant impedance contrast. Multiple peaks indicative of multiple impedance contrasts were present at some sites, and in most cases the longest period peak in the H/V data had the largest amplitude. There are a few possible situations in the Waikato area that could cause multiple peaks in the H/V data. 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. The longest period peak in the H/V data is likely to correspond to the fundamental mode vibration of the entire soil profile down to the basement greywacke rock.

A map of the site period estimates across the Waikato basin is presented in Figure 3. Most parts of the Waikato Basin, except very near the basin edge, have fundamental site periods longer than 0.6 seconds, which means they should be categorised as site class D at a minimum, according to NZS1170.5 (SNZ 2004). The measured site periods were over 5 seconds near Te Rapa and Gordonton, suggesting a deep sedimentary basin. 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. The geospatial variability in T_0 is consistent with the gravity anomaly of the region (FrOG Tech, 2011). These investigations are discussed in more detail in Jeong & Wotherspoon (2019).

Deep V_S profiles were developed at a site just to the west of Te Rapa Park, in one of the deeper parts of the basin as indicated by the H/V data. The field testing scope consisted of an active source array, three circular arrays with diameters of 50 m, 200 m and 500 m, and a 1500 m triangle.

The outputs of the inversion process are summarised in Figure 4 for the range of parameterisations, with the 1000 ‘best’ models shown for each. This provides a representation of the level of uncertainty in the V_S profile at this site, in the absence of any subsurface investigation data. Figure 4a) compares the experimental Rayleigh wave dispersion curve data with the theoretical dispersion curves. The inversion was fit to the fundamental mode dispersion curve, with the first and second higher mode theoretical dispersion curves also presented. The corresponding Love wave dispersion data is shown in Figure 4b), with no experimental Love wave data used to constrain the inversion process. The theoretical Rayleigh wave ellipticity curves and the theoretical 1D transfer function are compared against the experimental H/V data in Figure 4c) and d), respectively. The frequency of the peak in theoretical data compare well with the peak in the experimental data that is representative of the fundamental site period estimate.

The V_S profile for the overall depth range is presented in Figure 4e), and the near surface portion of the profile to a depth of 50 m in Figure 4f). The layering ratio of 7.0 is an outlier compared to the other data and was not considered in further analyses. The remainder of the layering ratios show a similar trend, with the spread in the profiles increasing at the base of the profile where the bedrock is encountered. Deep V_S profiles are being developed at a wider range of sites across the basin as part of other ongoing research.

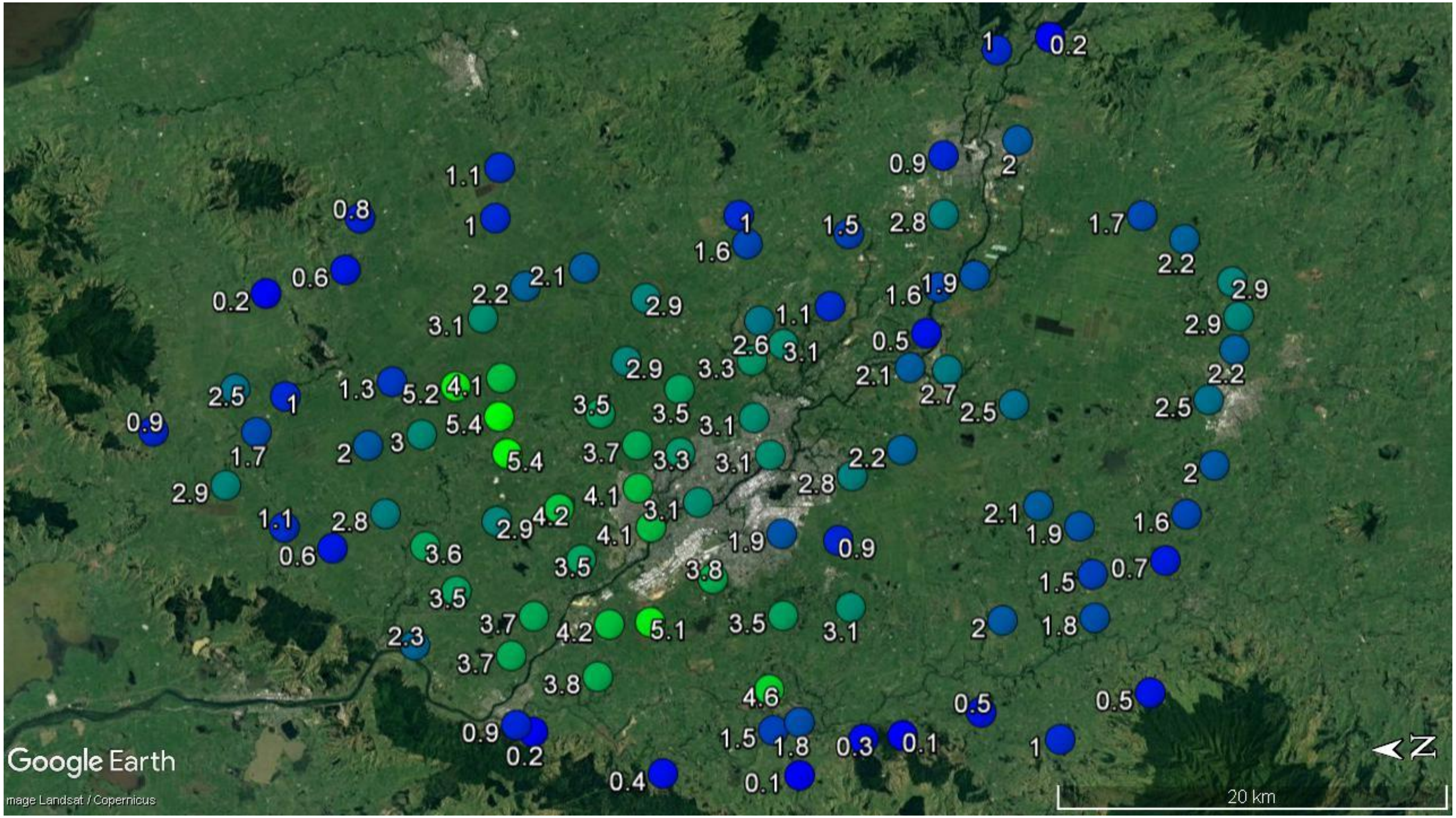

Figure 3. Site period estimates in the Waikato region.

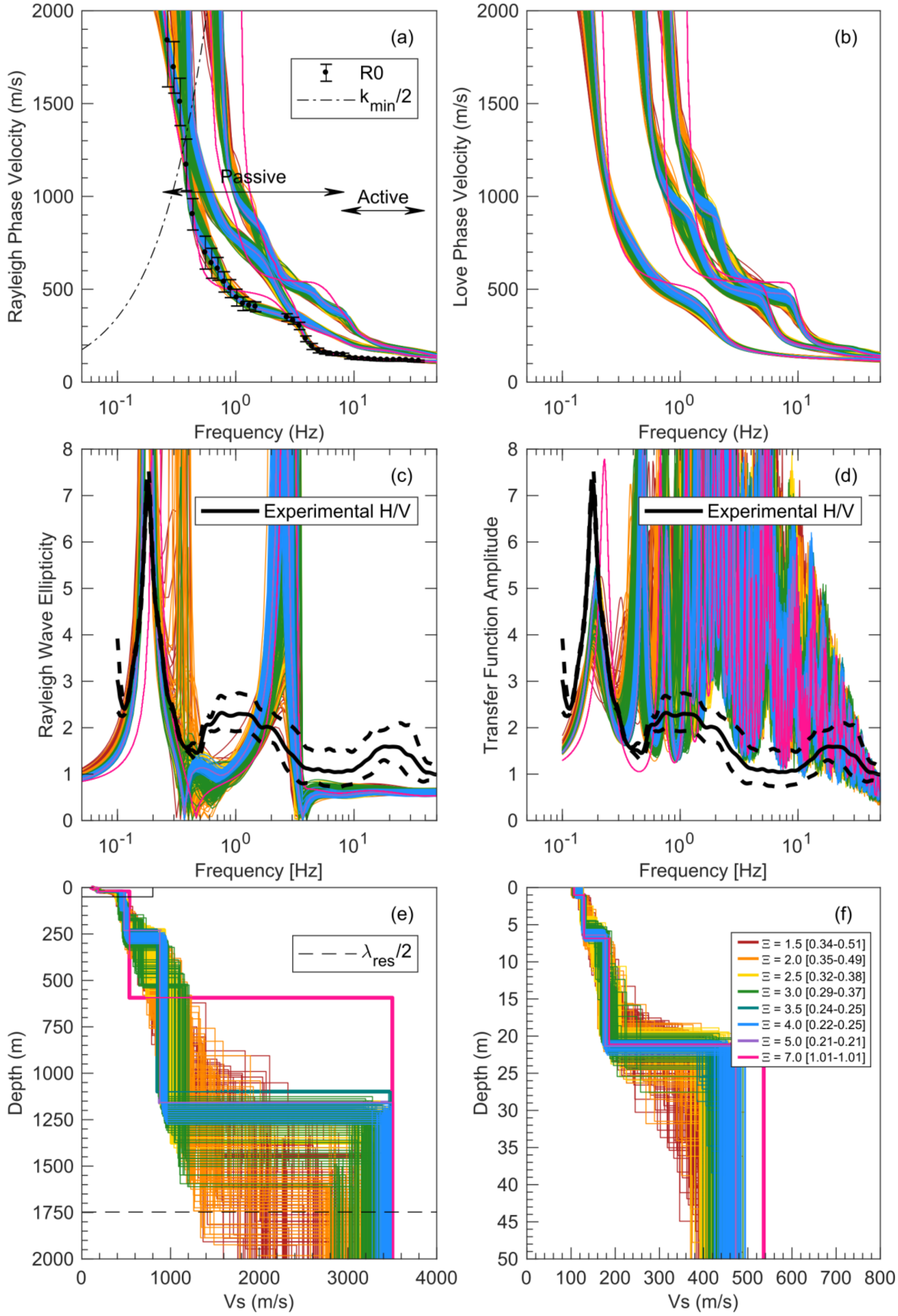

Figure 4. 1000 'best' models across the parameterisations used for the Waikato site. a) Rayleigh wave dispersion curves; b) Love wave dispersion curves; c) Rayleigh wave ellipticity curves and H/V data; d) empirical transfer function amplitude and H/V data; e) overall V_S profiles; f) V_S profiles to 50 m depth.

4.3 Hawke’s Bay

Site period estimates were collated at over 120 sites across the Hawke’s Bay, with a focus on the Heretaunga Plains. The majority of sites had a single peak in the H/V data, and the impedance contrast that these represented varied across the region. In some areas this peak likely represented the entire soil profile down to basement rock, while in other areas where a softer surface layer was present, this peak represented the profile above a shallow impedance contrast at the base of this surface layer. The sharpness of the peaks in the H/V data also varied across the region, which was inferred to be a result of the variability in the stiffness of soil deposits in the region.

From Meeanee in the south up to Bay View in the north the H/V peaks in Figure 5 and Figure 6 were likely representative of the fundamental period of the soil profile to bedrock. The variation in site period estimates aligned well with the topography of the surrounding hills and Bluff Hill. Locations more than a few hundred metres away from the base of Bluff Hill and around 400 m from the surrounding hills have fundamental site periods greater than 0.6 seconds, representative of a minimum of site class D according to NZS1170.5.

The amplitude of the H/V peaks in the region along the Napier city shoreline were less than the amplitude in areas further inland. Along the shoreline and throughout the downtown area of Napier is a deposit of beach gravel, stiffer than the surface deposits in other areas. This may have influenced the amplitude of the H/V peaks in this area.

South of Meeanee and across much of the remainder of the Heretaunga Plains some of the H/V peaks were likely representative of a shallower impedance contrast, and not the overall soil profile to bedrock. Figure 7 shows that this is the case in and around Hastings in the middle of the plains, with H/V peaks between 0.3 – 0.8 seconds. There are longer period peaks that may be representative of the overall soil profile to bedrock, these can be seen slightly further out from the central basin area that is dominated by softer near surface soil deposits.

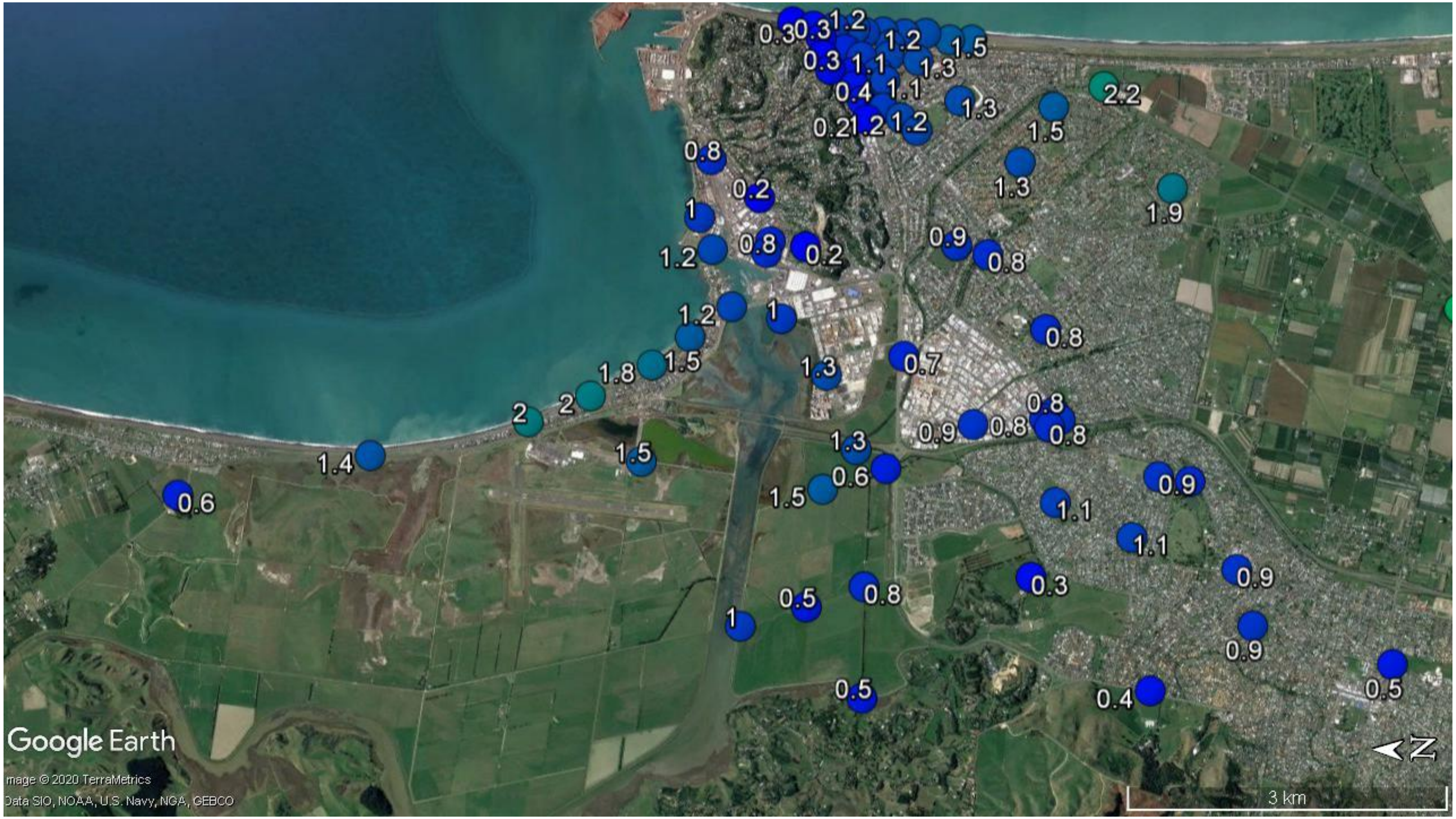

Figure 5. Site period estimates in the region surrounding Napier.

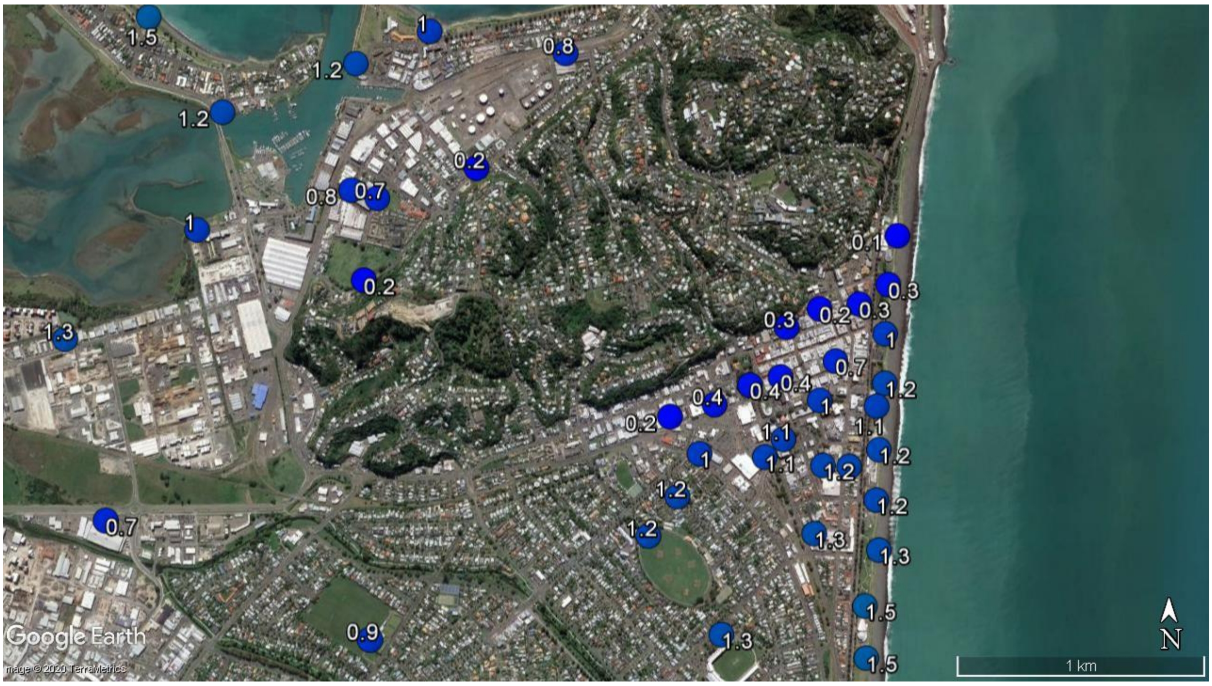

Figure 6. Site period estimates in the region surrounding central Napier.

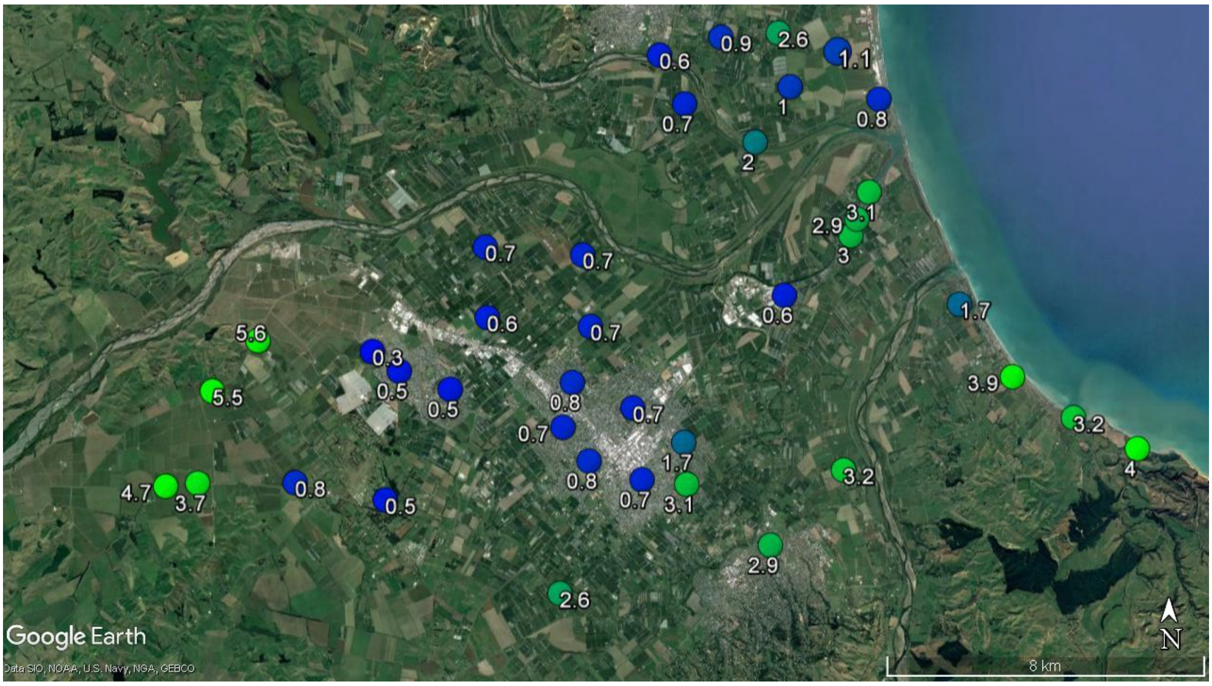

Figure 7. Combination of the period of the soil profile above a shallow impedance contrast and the overall soil profile above bedrock across the Hawke's Bay region.

Deep V_S profiles were developed at a site in Meeanee, in an area with deeper deposits than those to the north based on the H/V data. The field testing scope consisted of an active source array, and three circular arrays with diameters of 50 m, 200 m and 500 m.

The outputs of the inversion process are summarised in Figure 8 for the range of parameterisations, with the 1000 'best' models shown for each. Figure 8a) compares the experimental Rayleigh wave dispersion curve data with the theoretical dispersion curves. The inversion was fit to the fundamental mode dispersion curve, with the first and second higher mode theoretical dispersion curves also presented. The corresponding Love wave dispersion data is shown in Figure 8b), with experimental Love wave data used at this site to further constrain the inversion process. The theoretical Rayleigh wave ellipticity curves and the theoretical 1D transfer function are compared against the experimental H/V data in Figure 8c) and d), respectively. The peaks in theoretical data at 0.3 Hz is likely representative of the fundamental response of the overall soil profile above rock. There looks to be a good comparison with the 1D transfer function, with a peak in this data near to this frequency. The comparison is not as clear for the Rayleigh wave ellipticity data, although there is some evidence of a peak.

The V_S profile for the overall depth range is presented in Figure 8e), and the near surface portion of the V_S profile to a depth of 75 m in Figure 8f). The layering ratios show a fairly similar trend, with the spread in the profiles increasing at the base of the profile where the bedrock is encountered.

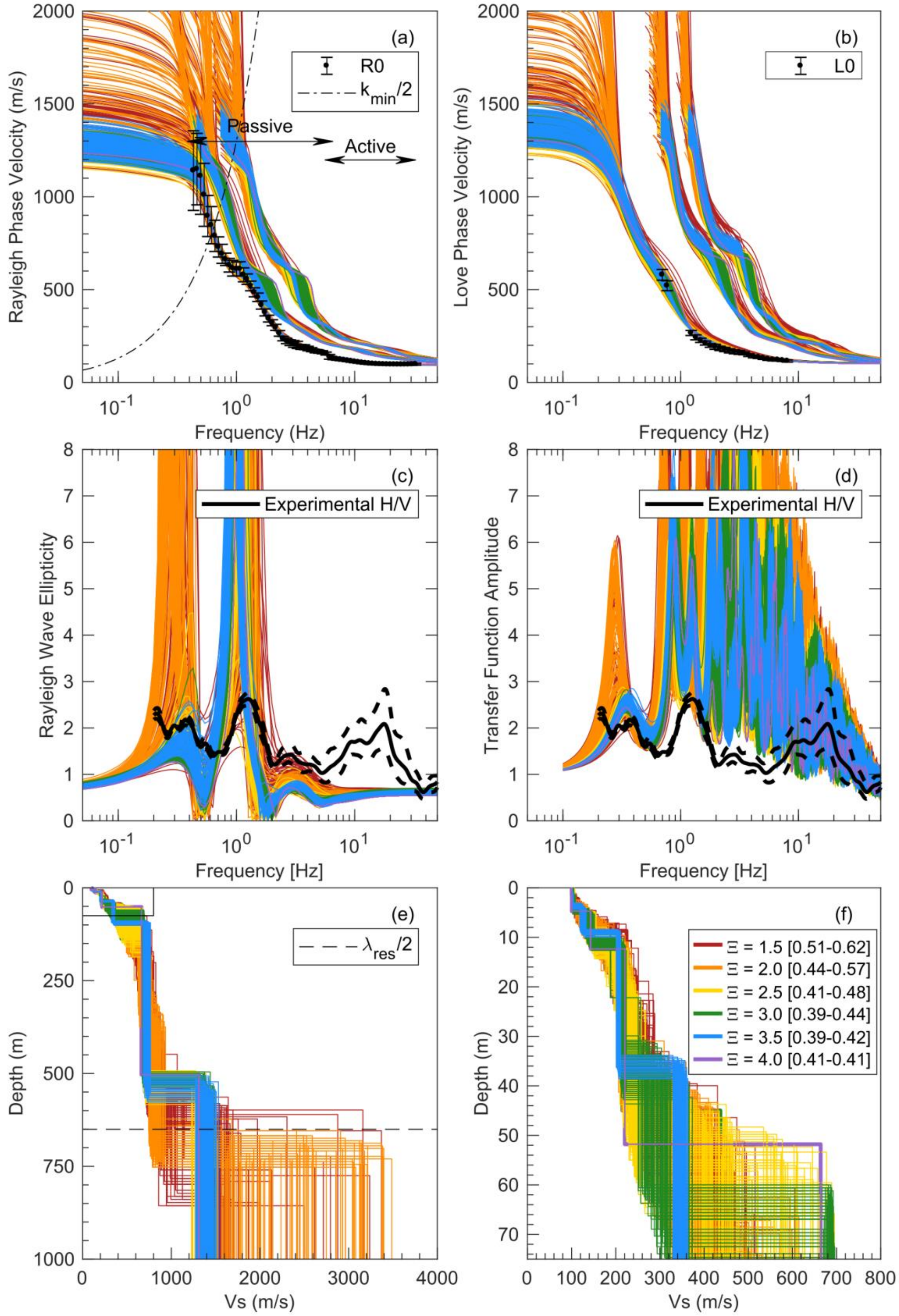

Figure 8. 1000 'best' models across the parameterisations used for the Hawke's Bay site. a) Rayleigh wave dispersion curves; b) Love wave dispersion curves; c) Rayleigh wave ellipticity curves and H/V data; d) empirical transfer function amplitude and H/V data; e) V_S profiles; f) V_S profiles to 50 m depth.

5 Basin Modelling Methodology

Basin models have been classified into four type groups, based on the type, quality and quantity of the input data and the rigour of the modelling techniques employed in the development of the model. We have foucsed on models that capture the dynamic characteristics of the basin relevant to ground shaking. Type 1 basin models are the simplest of the basin models, developed using geologic maps and topographic data from digital elevation models. Type 2 basin models include limited field datasets, such as sparse map of H/V spectra ratios and a few deep V_S profiles from surface wave testing. Type 3 basin models are developed using large, high-quality field datasets. For example, a Type 3 basin model may include a dense grid of hundreds of H/V spectral ratios, several deep V_S profiles, P-wave reflection lines, and deep boreholes. Type 4 models are the most complex, combining extensive geological, geotechnical, and geophysical datasets with advanced modelling techniques. These robust models include a well-defined soil/bedrock interface and a well-characterised sedimentary profile across the basin. Figure 9 and Table 2 give examples of the types of basin characterisation at different locations across New Zealand. Existing models that would be considered detailed, using a range of geologic, geotechnical and geophysical datasets, have been developed for Canterbury (Lee et al. 2017), Wellington (Semmens et al. 2010, Kaiser et al. 2019) and Lower Hutt (Boon et al. 2011).

Simple basin models (e.g., Type 1 and Type 2) can be refined and upgraded as data from site characterisation studies are incorporated into the basin model. Through the use of the H/V method and other geophysical testing methods, the 'rapid' basin model development methodology, described herein, provides a means to quickly improve existing Type 1 basin models and develop new basin models in other regions.

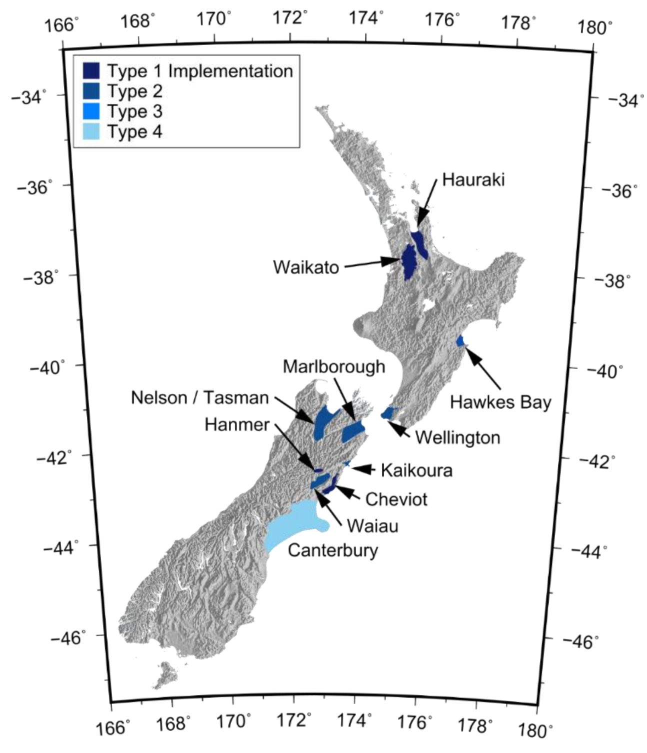

Figure 9. Examples of existing basin models across New Zealand.

Table 2. Summary of examples of existing basin models across New Zealand.

Type 1	Type 2	Type 3	Type 4
Cheviot	Kaikoura		Canterbury
Hanmer	Marlborough		Wellington CBD
Waikato	Nelson/Tasman		Lower Hutt
Hauraki	Waiau		
Napier	Upper Hutt		

5.1 Topography-based Method

Simple (e.g., Type 1) basin models require the definition of the horizontal extent (i.e., basin edge) along the ground surface and a 3D surface (e.g., northing, easting, and depth) along the soil/bedrock interface. The topography-based method is used to develop these simple basin models by using the slope of topographic features (e.g., rock outcrops, hills, ridges, mountains) surrounding and within the basin to infer the geometry of the soil/bedrock interface, especially when additional field data is unavailable.

For the Type 1 models presented in this study, the basin edge is defined by examining geologic maps describing surface geology of the basin. Published hardcopies and digital files of geologic maps of New Zealand at 1:250,000 scale (Q-MAPS) are available from GNS and were used for this project. The boundary between the sediments (e.g., soil) within the basin and the rock surrounding the basin may be identified and traced on the geologic map. Outcrops of rock within the sedimentary basin should also be identified and outlined.

The topography of the ground surface is described by digital elevation models (DEMs), which contain elevation data associated with a grid in terms of Northing and Easting (or Latitude and Longitude). The Shuttle Radar Topography Mission (SRTM) is a high-resolution DEM dataset, which contains elevation data across the globe at a 1 arc-second (approximately 30 metre) resolution and has been made publically available by the USA NASA and JPL.

MOVE, a structural geology modelling software developed by Petroleum Experts Limited, is used to combine the geo-referenced geologic maps and DEMs to develop basin models.

The outlines of the basin edge and all interior rock outcrops are digitally traced on the geologic maps in MOVE, as illustrated in Figure 10 for the Waikato and Hauraki sedimentary basins. These outlines are used to trim the portion of the ground surface DEM associated with the sediments in the basin. Thus, only the topographic information associated with the rock surrounding the basin and the rock outcrops within the basin are retained.

Topography is used to infer the slope of the soil/bedrock interface near the ground surface. However, the depth to the bedrock in the middle of the basin is poorly constrained. Based on slope of the topography alone, the basin would be conical in shape (as opposed to bowl shaped) and may not be realistic. Thus, any available geologic data (such as cross sections and projected fault lines from the geologic map, deep boreholes) is used to develop multiple cross sections across the basin with outlines indicating the inferred soil/bedrock interface. To adequately constrain the 3D surface, several cross sections defined in approximately orthogonal directions (e.g., North/South and East/West) are needed and should be spaced no more than 10 to 20 km apart, depending the lateral extent of the sedimentary basin. Defining these cross sections for the initial basin models is inherently subjective and is dependent upon judgment of the modeller.

In MOVE, the outline of the basin edge, the topographic data of surrounding rock and interior rock outcrops, and the cross sections are combined to provide constraint for a kriging algorithm, which interpolates the available data and evaluates the depth to the soil/bedrock interface along a pre-defined horizontal grid (Figure 11). The grid points are typically spaced 100 to 1,000 metres apart depending upon the quality of the input data and the lateral extent of the basin (i.e., the land area modelled). The kriged 3D surface representing the soil/bedrock interface is exported from MOVE and is suitable for use in a Type 1 basin model. As noted above, the depth to the soil/bedrock interface is poorly constrained by the topographic data and can by improved through the inclusion of geophysical data.

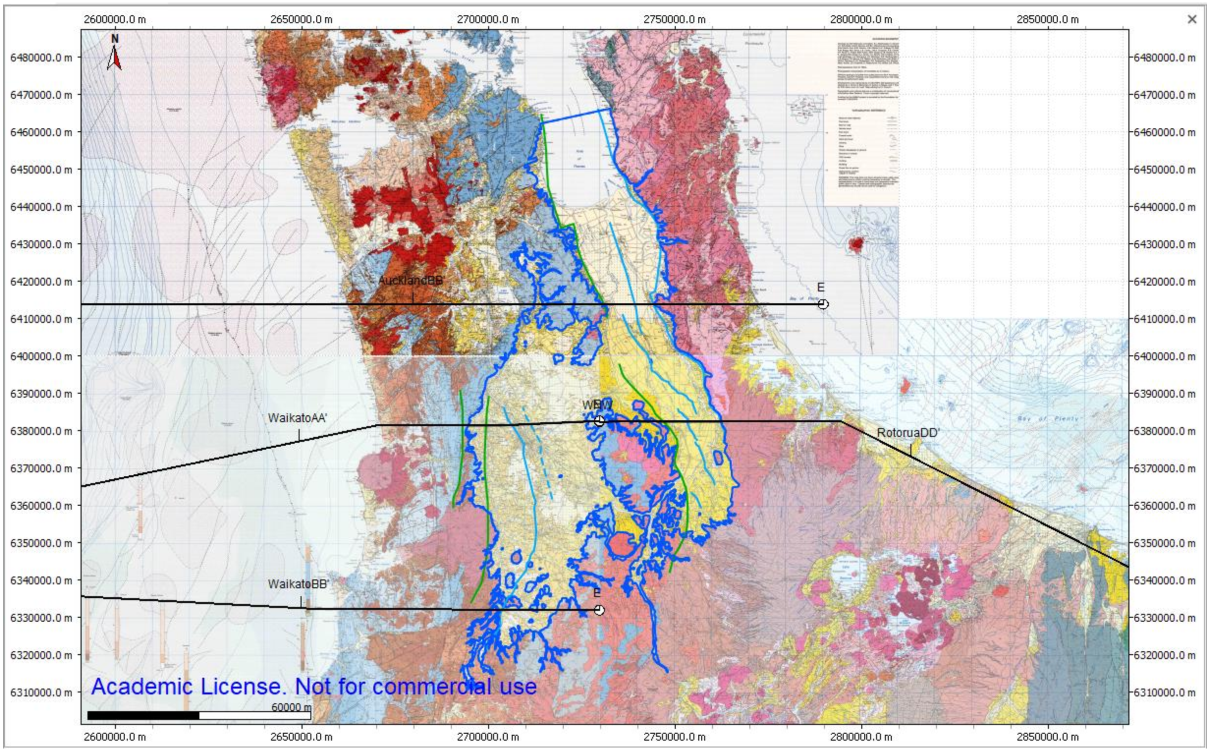

Figure 10. Example MOVE project with combination of datasets and the outline of the edge of the Waikato and Hauraki Plains basins.

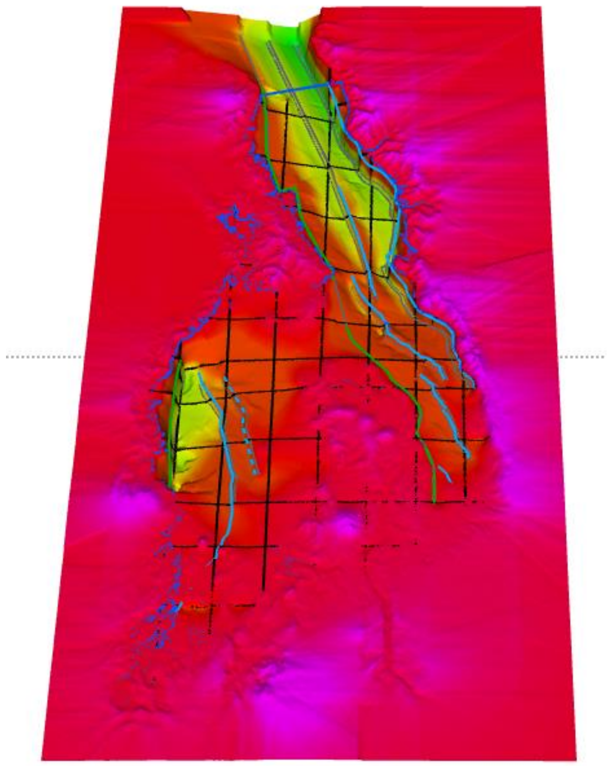

Figure 11. Example kriged 3D surface of the soil-rock interface within the Waikato and Hauraki Plains basin areas and the surrounding topography.

5.2 ‘Rapid’ Method

A primary objective of this research is to facilitate the rapid development of sedimentary basin models in New Zealand through the use of site characterisation data from geophysical testing, improving upon topography-based and geology-based models by providing constraint to the bedrock/soil interface and the characterisation of local velocity structure. This ‘rapid’ basin model method combines site period estimates from ambient vibration H/V spectral ratio testing with V_S profiles from deep surface wave testing to estimate the depth to bedrock (i.e., the basin basement) using (1) the quarter wavelength method and (2) transfer functions from 1D linear elastic site response analyses. Using both of these analytical methods, basin (or sub-basin) specific relationships between bedrock (basement) depth and site period (D-T_0) may then be used to quickly map the basin basement.

The best V_S profiles from deep surface wave testing were used to develop the D-T_0 relationships and attributed to the nearest (e.g., local sub-basin) or basin-wide site period measurements depending upon surface wave testing data available. Specifically, V_S profiles from the inversion(s) most representative of any supporting geotechnical data, local geologic knowledge, and/or the most reasonable layering ratio parameterisation with the lowest inversion misfit were used. When available, multiple V_S profiles were used to develop the local D-T_0 relationships, typically the 1000 ‘best’ V_S profiles with the lowest inversion misfit. Furthermore, an impedance contrast corresponding to the soil/bedrock interface must be present in the V_S profiles. The aperture of the surface wave testing arrays must be wide enough to resolve deep layers and the velocity of the deepest rock layer should be greater than 750 m/s (i.e., the V_S of a weathered rock).

For both the quarter wavelength and transfer function methods, the D-T_0 relationships were developed through specification of the basement depth, adjustment of the velocity profiles, and the evaluation of the corresponding site period. The basement depth was systematically increased from near the ground surface to a value greater than the maximum anticipated depth of the sedimentary basin. Typically, trial basement depths ranged from 1 to 2,000+ metres, depending on the basin. An individual V_S profile was adjusted by assigning the trial basement depth to the top of the half-space (i.e., bedrock layer). The original V_S of the half-space from the velocity profile was retained, only the depth to the top of this layer was adjusted up or down, as shown in Figure 12. If the trial basement depth was greater than the depth to top of the half-space in the initial velocity profile, the thickness of the sedimentary layer above the half-space was increased accordingly, as shown in Figure 12b). Likewise, if the trial basement depth was shallower than the initial half-space depth, the thickness of the overlying sedimentary layer was decreased. If the trial basement depth was shallower (i.e., less than) the depth to the top of any overlying sedimentary layers in the initial velocity profile, each of those layers and their corresponding V_S were removed from the adjusted velocity profile, as shown in Figure 12c). Effectively, this methodology assumes that the sediments within the basin were deposited in horizontal layers with uniform layer thickness across the sedimentary basin, similar to an idealised layer cake in a bowl. While this assumption is an oversimplification and not truly representative of natural sedimentation processes, it simplifies the calculations and enables the development D-T_0 relationships that can readily and uniformly be applied across a basin.

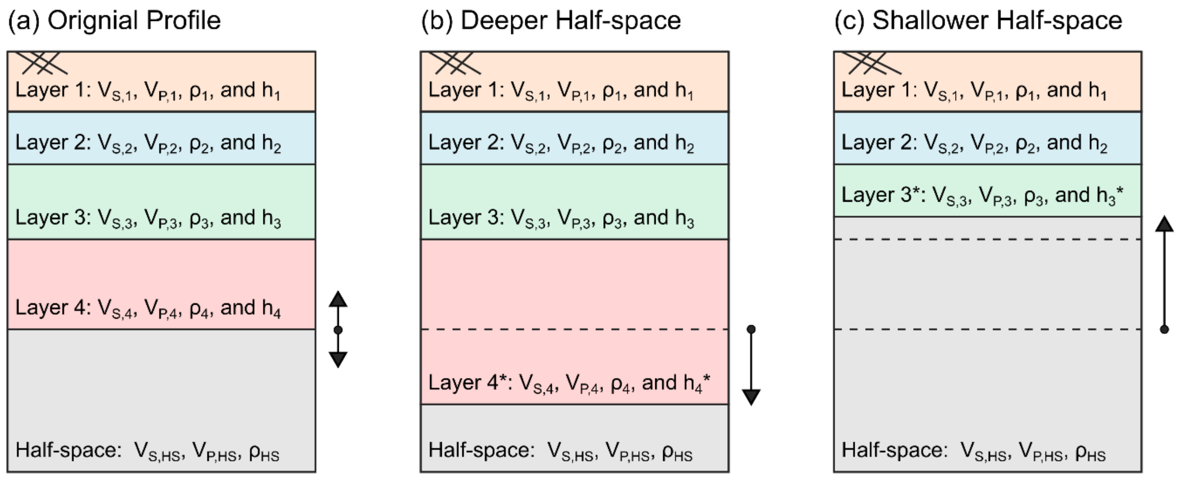

Figure 12. Schematic of the methodology used to develop representative V_S profiles at each T_0 measurement location. a) original V_S profile; b) V_S profile with deeper half-space; and c) V_S profile with shallower half-space. * indicate layers with modified thicknesses.

The simplest basement depth-site period relationship is the quarter-wavelength equation (Equation 1), which is commonly used to evaluate site period given a V_S profile above an impedance contrast or bedrock.

$$T_0 = 4H/V_{S,avg} \qquad (1)$$

where H is the thickness of the soil profile (i.e., the trial basement depth) and $V_{S,avg}$ is the time-averaged V_S profile over that thickness. The time averaged-averaged V_S was evaluated using Equation 2.

$$V_{S,avg} = \frac{\sum_{n=1}^{N} h_i}{\sum_{n=1}^{N} \frac{h}{V_{S,i}}} = \frac{h_1 + h_2 + \cdots + h_N}{\frac{h_1}{V_{S,1}} + \frac{h_2}{V_{S,2}} + \cdots + \frac{h_N}{V_{S,N}}} \tag{2}$$

where h_i is the thickness and $V_{S,i}$ is the shear wave velocity of an individual soil layer in the V_S profile. Note that the time-average V_S includes all of the soil layers above the half-space (bedrock), but does not include the half-space itself. The trial basement (i.e., half-space) depths and the associated time-averaged V_S (from the associated adjusted V_S profiles) were input directly in Equation 1 to develop the quarter wavelength D-T_0 relationship.

Another approach to estimate the fundamental site period is to evaluate the 1D linear elastic transfer function between the ground surface and the top of the bedrock from an associated V_S profile. As ambient vibrations induce negligible shear strain on the basin soils, the experimental site periods from H/V testing may be compared to the fundamental site periods evaluated from a 1D linear elastic transfer functions. These transfer functions were calculated analytically as outlined in Kramer (1996) for a 1D layered, damped soil profile on elastic rock. Unit weights were assigned to each soil layer based on local geotechnical data or assigned reasonable values based on soil type. The small-strain soil damping ratios were assigned based on Darendeli (2001) and a small-strain damping ratio of 0.5% was assigned to the bedrock. A 1D linear elastic transfer function was calculated for each trial basement depth and the associated suite of adjusted V_S profiles. The fundamental frequency (or period) of vibration for the soil profile is associated with the lowest frequency (highest period) peak of the transfer function, as illustrated in Figure 13. As the peak associated with the fundamental period can be numerically identified and a closed-form equation for the 1D linear elastic transfer function exists, this transfer function D-T_0 relationship may be automated to evaluate the site period for a range of trial basement depths.

Both the quarter wavelength and transfer function methodologies produce a D-T_0 relationship for a single V_S profile input which is adjusted/truncated for each trial basin basement depth. Whenever a suite of shear wave velocity profiles was available, such as the ‘1000 best’ deep V_S profiles from a surface wave inversion, the D-T_0 relationships were evaluated for each individual V_S profile, producing a suite of D-T_0 relationships. For each trial basement depth, the median of the fundamental site period was calculated and used to develop the median D-T_0 relationships for estimation of the depth to bedrock across each sedimentary basin. Example quarter wavelength and transfer function D-T_0 relationships are shown in Figure 14 for the Waikato Basin. The median D-T_0 relationships were developed using a suite of the 1000 best shear wave velocity profiles from the LR = 3.5 inversion parametrisation.

These quarter wavelength and transfer function D-T_0 relationship, based upon deep surface wave testing V_S profiles, coupled with a map of fundamental site periods inferred from ambient vibration H/V testing enables the ‘rapid’ development of sedimentary basin models from quick, non-invasive geophysical testing programmes. This ‘rapid’ basin model development method builds upon the topography-based methodology by providing constraint to the depth of the soil/bedrock interface and the inclusion of local, basin-specific V_S profiles.

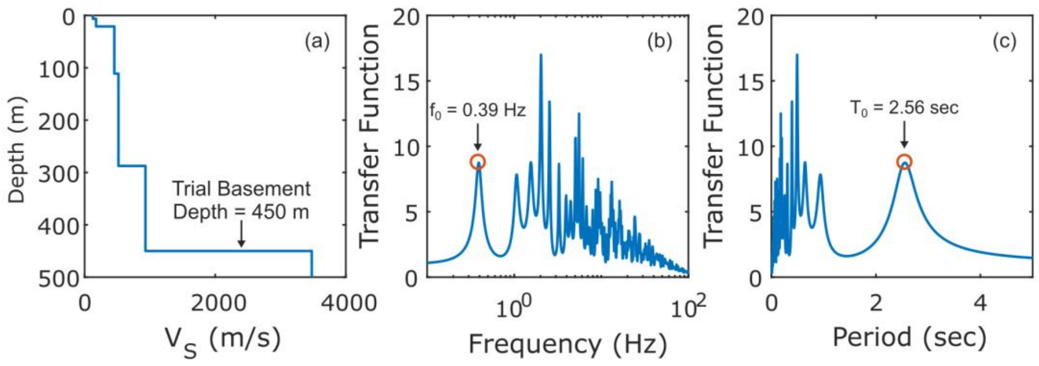

Figure 13. Example transfer function and interpretation to pick the peak associated with the fundamental site period.

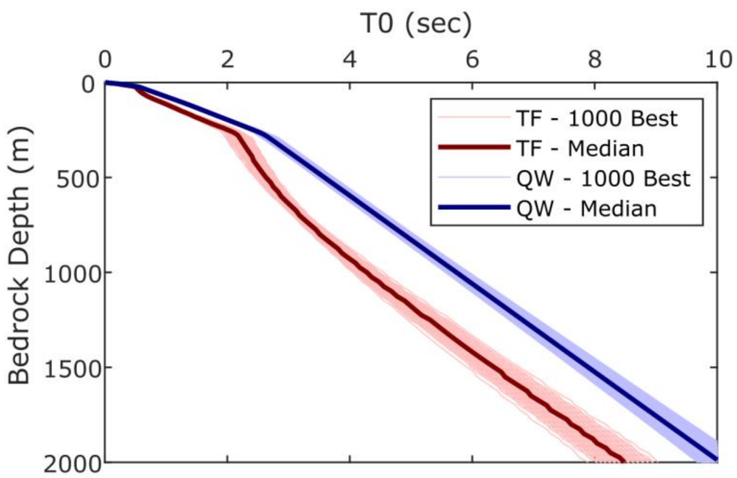

Figure 14. Example D-T_0 relationships using the transfer function and quarter wavelength approach.

6 Basin Model Development and Validation

This section provides a summary of the basin models that have been developed in the case study locations across New Zealand using the ‘rapid’ approach discussed in the previous section. In order to assess the effectiveness of the proposed method, in some locations the ‘rapid’ basin model approach was compared against basin models developed using other approaches.

The following case study locations are presented, with the models that have been used for validation summarised:

- Hawke’s Bay – no published model
- Hauraki Plains – Type 1 model
- Waikato – Type 1 model
- Canterbury – Type 4 model

6.1 Comparison of D-T_0 Models

The D-T_0 models for the different sedimentary basins across NZ are presented in Figure 15. The Hawkes Bay and Waikato models were developed using the deep V_S profiles developed as part of this study, while the models for Canterbury were developed using the deep V_S profiles from Deschenes et al. (2018). In the near surface the depths estimated are similar as these are calculated using a single V_S layer, where the quarter wavelength and transfer function approach should give similar outputs. At longer periods the transfer function approach estimates deeper bedrock than the quarter wavelength approach at all locations.

The D-T_0 relationships for Canterbury have the greatest depth estimates at each T_0 value, due to the presence of stiff gravel deposits from the ground surface at this profile location. V_S has a gradual increase with depth, and the basement in this location is in excess of 1500 m. This gradual increase is the reason that the D-T_0 relationships for the quarter wavelength and transfer function approaches are quite similar.

The D-T_0 relationships for Hawke’s Bay and Waikato both have much shallower depth estimates for smaller T_0 values, as in both regions there are fairly soft near surface deposits. As the profile shifts into deposits with higher V_S values, there is clear change in the slope of the D-T_0 relationships, and this change results in a divergence of the quarter wavelength and the transfer function relationships. The averaging of the V_S over the entire profile means the slope change is not as significant as that seen for the transfer function approach. In Hawkes Bay, there are stiff deposits at approximately 100 m depth, meaning there is a larger increase in depth as T_0 increases. In Waikato, the profile has a significant increase in stiffness at approximately 300 m depth, and it is here that the depth starts to increase at a faster rate compared to T_0.

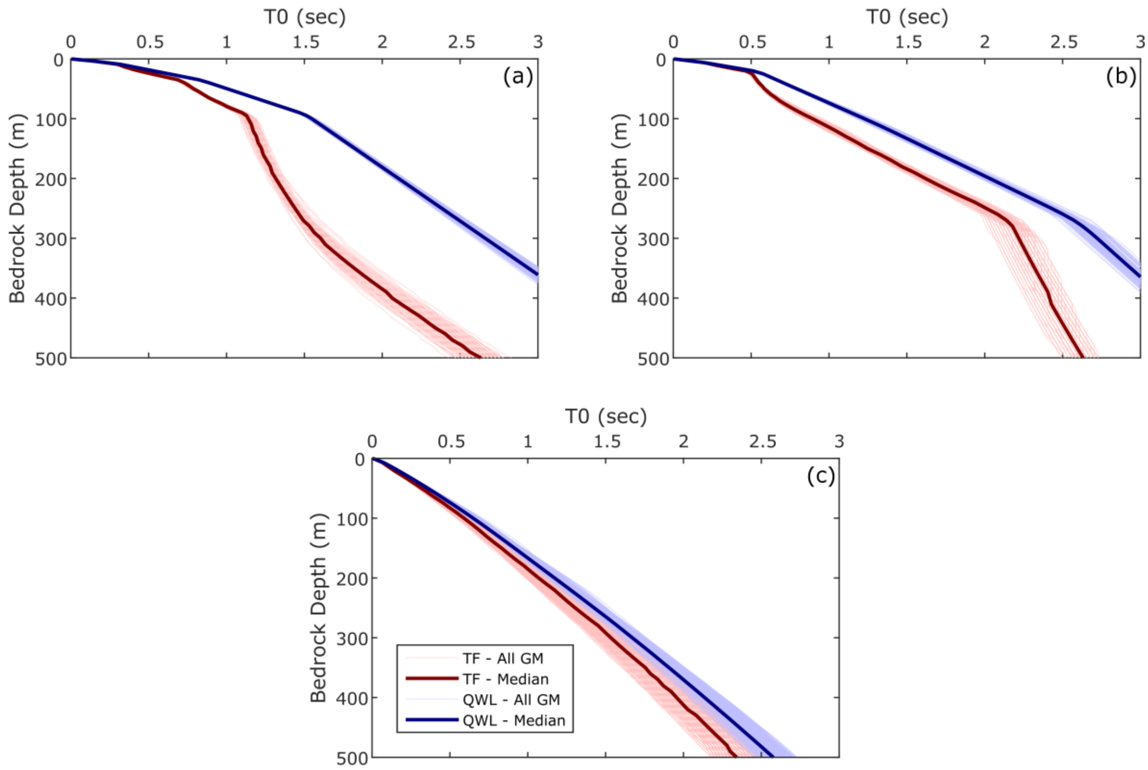

Figure 15. Comparison of the D-T_0 models for different regions across New Zealand a) Hawke's Bay; b) Waikato; c) Canterbury.

6.2 Hawke's Bay

No published basin models for the Hawke's Bay region are currently available (this is currently in preparation, Begg et al. in prep), nor has a Type 1 topography-based model been developed using the methodology described above. However, geophysical method-based site characterisation efforts were a part of the research described herein. Thus, the region has presented an opportunity to employ the 'rapid' basin model development method.

In the Hawkes Bay region, the H/V peaks from testing around Napier, from Meeanee in the south to Bay View in the north, are likely most representative of the fundamental site period of the soil profile to bedrock. The Meeanee V_S profiles characterise the deepest soils and the bedrock in the area of interest and were used to develop the quarter wavelength and transfer function-based D-T_0 relationships (Figure 15a)).

The map of the fundamental site periods and the Meeanne D-T_0 relationships were used to estimate the depth to bedrock in the Napier sub-region. The basement depth maps in Figure 16 generally follow expected trends, based on surrounding topographic features. The basin is shallowest along the sides of the Bluff Hill (an outcrop of rock) and near the western hills. Conversely, the basin is deepest in the flat areas and along the coast to the north (e.g., the Bay View area) and to the south (e.g., Meeanee and Awatoto) of Napier.

At site periods less than 0.75 s the two D-T_0 relationships are similar (refer to Figure 15a)) and, therefore, the basin basement maps agree where the bedrock is shallow (e.g., along Bluff Hill).

However, as discussed previously, at long periods the transfer function approach estimates deeper bedrock than the quarter wavelength approach. The difference is greater than 200 metres in the deepest portion of the sedimentary basin near Meeanee. As noted above, the deep V_S profiles were developed from surface wave testing at a farm site in Meeanee. Thus, the transfer function approach, as applied to the nearby H/V site period estimates, agrees better with the depth to bedrock in the V_S profiles. However, away from Meeanee the depth to the bedrock is likely bracketed by the two approaches considered in the 'rapid' method.

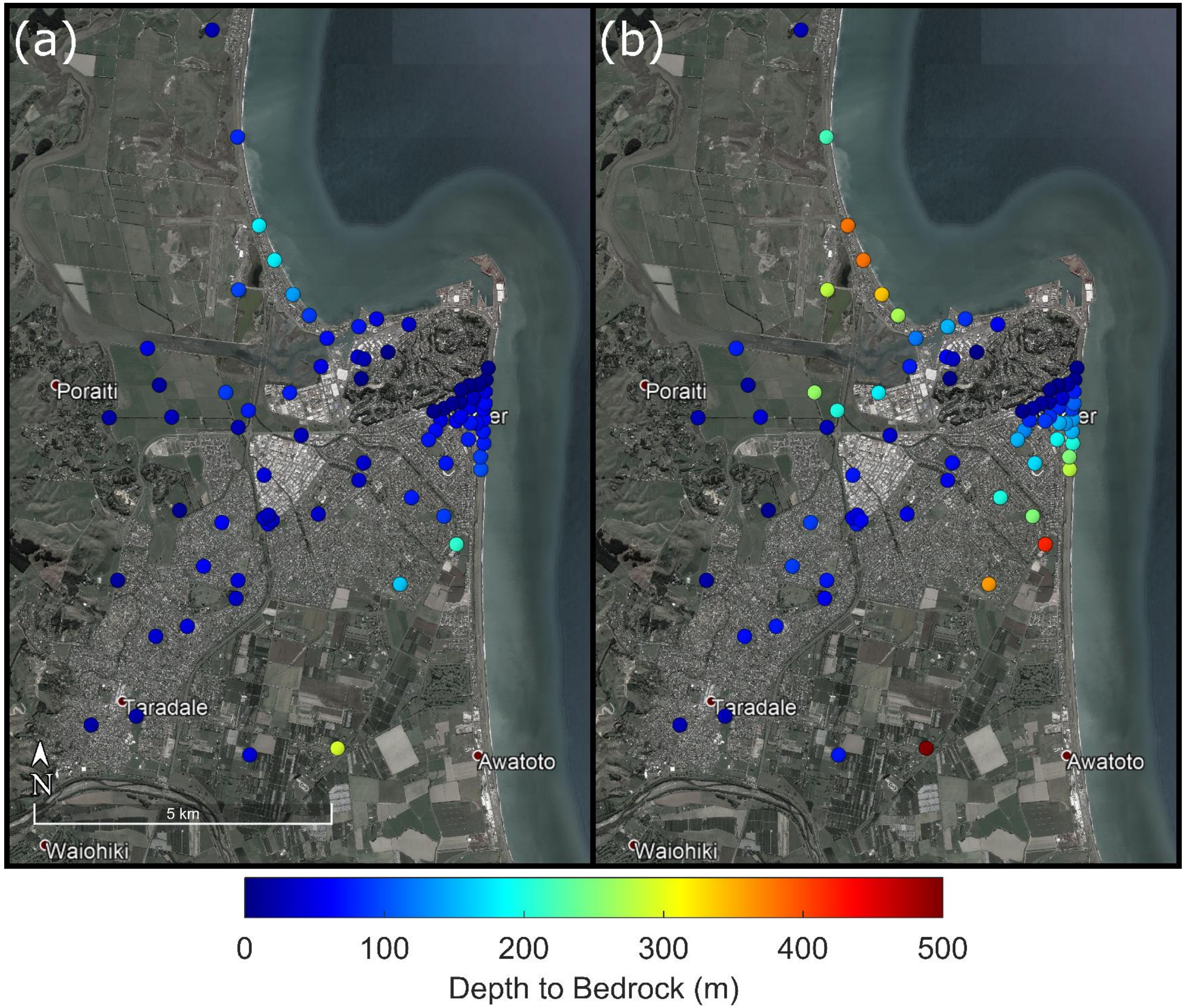

Figure 16. Basin depth characteristics in the Hawke's Bay region – Napier focus*:* (a) Rapid model using the quarter wave length approach; (b) Rapid model using the transfer function approach.

6.3 Hauraki Plains

As part of this project, a Type 1 topography-based model was developed for the Hauraki Plains, using the Auckland, Rotorua, and Waikato geologic Q-maps and digital elevation models from the Shuttle Radar Topography Mission. Two cross sections from the Auckland and Rotorua Q-maps were used to constrain the basin basement across the entire basin. The DEM was used to constrain the near-surface slope of the basin basement along the edges of the basin and interior rock outcrops. Thus, the depth to bedrock was generally poorly constrained, especially in areas with significant faulting. The 'rapid' basin model method was compared against this Type 1 topography-based model for the region.

In the Hauraki Plains, the H/V peaks, are likely most representative of the fundamental site period of the soil profile to bedrock. As there was no deep shear wave velocity profiles developed for the Hauraki Plains, the profile from the Waikato Basin was used to represent the soils in the region and develop the quarter wavelength and transfer function-based D-T_0 relationships (Figure 15b)). This is not an ideal approach, but as there are some similarities in the deposits in each region, it is appropriate for the testing of this methodology. Basin specific profiles will be collated in the near future to further revise these models.

Together, the map of the fundamental site periods and the Waikato D-T_0 relationships were used to estimate the depth to bedrock in the Hauraki Plains. The basement depth maps in Figure 17b) and c) follow similar trends, with the shallowest locations on each side of the basin, followed by the central portion of the basin that follows the shallow ridge part of the half graben structure. In these regions the estimated depth is similar, due to the similar D-T_0 relationships in the short site period range. The difference between the two D-T_0 relationships becomes more significant in the deepest parts of the sedimentary basin, as a result of the divergence of the two at larger depths.

The Type 1 model in Figure 17a) has some similar features to those from the 'rapid' method. The main difference is the variation of depth on the eastern edge of the plains. Adjacent to the Coromandel Ranges, the depths are the largest, which is a result of the extension of the steep topography of the Ranges into the basin. These depth estimates are much larger than those from the 'rapid' method, and do not agree well with the gravity survey derived depth from Hochstein & Nixon (1979). This model would therefore need further constraint based on these other datasets.

In the central and western parts of the plains, there is better agreement in the variation in depth between the D-T_0 relationships and the Type 1 model. The shallow depths in the western and central areas, and the greater depths between these areas is evident across all models. There is better agreement between the Type 1 model and the transfer function based depths, with greater depth estimates for the Type 1 model.

There is clearly a large amount of scatter in the overall comparison of basin depth estimates from the Type 1 model and the 'rapid' approaches in Figure 18. If the points representative of the region to the east of the basin where the match is poor were removed (with both rapid depth estimates less than 400 m and Type 1 depth estimates greater than 400 m), the comparison is slightly improved. The transfer function based estimates have a better correlation to the Type 1 model than the quarter wavelength estimates.

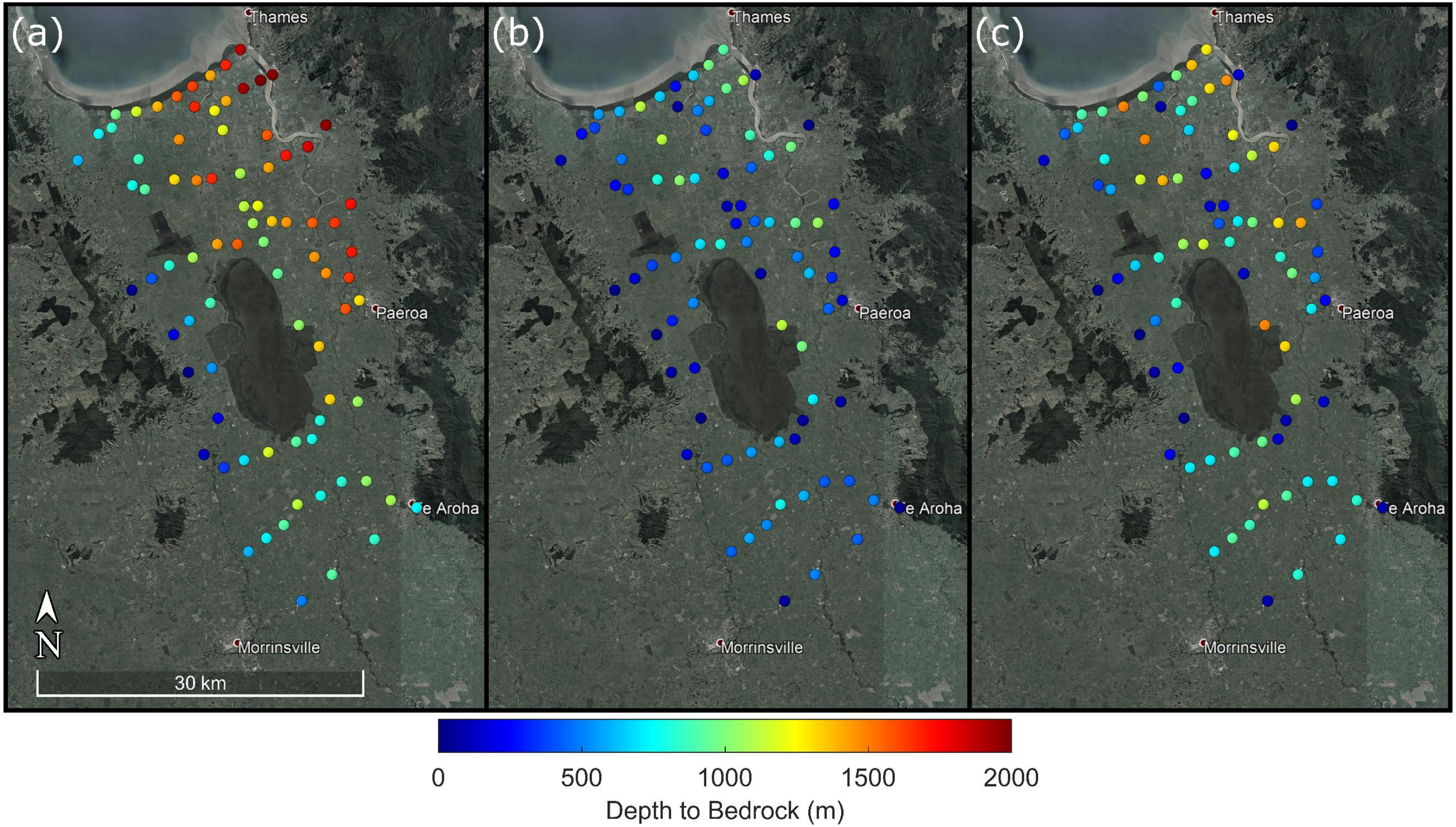

Figure 17. Basin depth characteristics in the Hauraki Plains region: (a) Type 1 model; (b) Rapid model using the quarter wave length approach; (c) Rapid model using the transfer function approach.

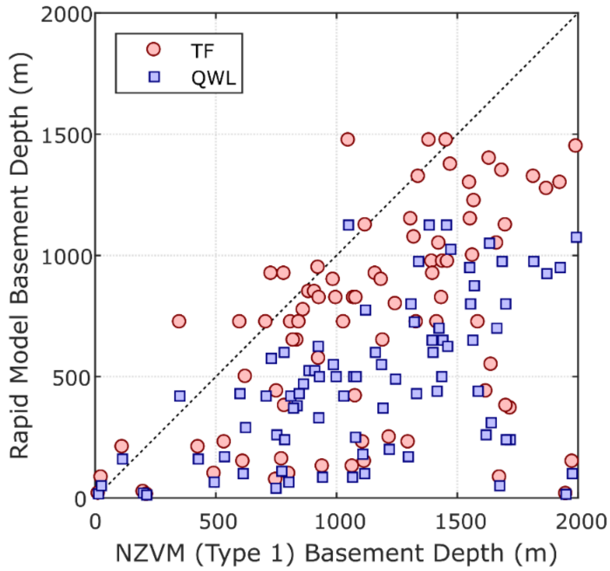

Figure 18. Comparison of Hauraki Plains basin depths from the 'rapid' method and Type 1 model.

6.4 Waikato

As part of this project a Type 1 topography-based model was developed for the Waikato Basin, using the Waikato and Auckland geologic Q-maps and digital elevation models from the Shuttle Radar Topography Mission. Two cross sections from the Waikato Q-map, based on deep boreholes, were the only data constraints on the depth to bedrock across the basin. The DEM was used to constrain the near-surface slope of the basin basement along the edges of the basin and interior rock outcrops. Thus, the depth to bedrock was generally poorly constrained. The 'rapid' basin model method was compared against this Type 1 topography-based model for the region.

In Waikato, the H/V peaks are likely most representative of the fundamental site period of the soil profile to bedrock. Deep shear wave velocity profiles developed from the site near Te Rapa Park was used to represent the soils in the region and develop the quarter wavelength and transfer function-based D-T_0 relationships (Figure 15b)). Together, the map of the fundamental site periods and the Waikato D-T_0 relationships were used to estimate the depth to bedrock in Waikato.

The basement depth maps in Figure 19b) and c) follow similar trends, with the shallowest locations along the edge of the basin, and the deepest locations along a SW to NE trend in an area just to the north of the Hamilton urban area. This trend aligns with the orientation of faulting in the region identified in previous studies (Moon & de Lange 2017). Along the edge of the basin the estimated depth is similar, due to the similar D-T_0 relationships in the short site period range. The difference between the two D-T_0 relationships becomes clear in the deepest parts of the sedimentary basin, as a result of the divergence of the two relationships at larger depths. The greatest depth estimated by the transfer function approach is approximately 1300 m near Te Rapa and Gordonton, compared to 1000 m for the quarter wavelength approach.

The Type 1 model in Figure 19a) has some similar general features to those from the 'rapid' method. The depths on the northern, eastern and southern edges of the basin have comparable values, likely a result of shallow sloping hills surrounding these areas propagating a shallow basin slope and slowly increasing depth with distance away from the hills. The main difference is the variation of depth in the western part of the basin, where the depths are the largest due to the extension of the surrounding topography into the basin. The greatest depths estimated by this approach is approximately 500 m greater than the transfer function approach. The deepest part of the basin for the Type 1 model is also in quite a different location to that estimated by the D-T_0 relationships. Comparison of the basin depths with the depth of petroleum boreholes in the region suggests that the transfer function approach is a better representation of the basin depth (Jeong & Wotherspoon 2019).

All basin depth estimates from the Type 1 model and the 'rapid' approaches are compared in Figure 20. This shows that there is a general agreement between the Type 1 model and the transfer function based depths. The quarter wavelength based depths are much lower in general, and this is evident in the lower trend of these points in the figure. There is a lower trend of points where the agreement is not as good, where the Type 1 model depths are much greater than those estimated by the 'rapid' approach. These correspond to point in the western part of the basin discussed previously.

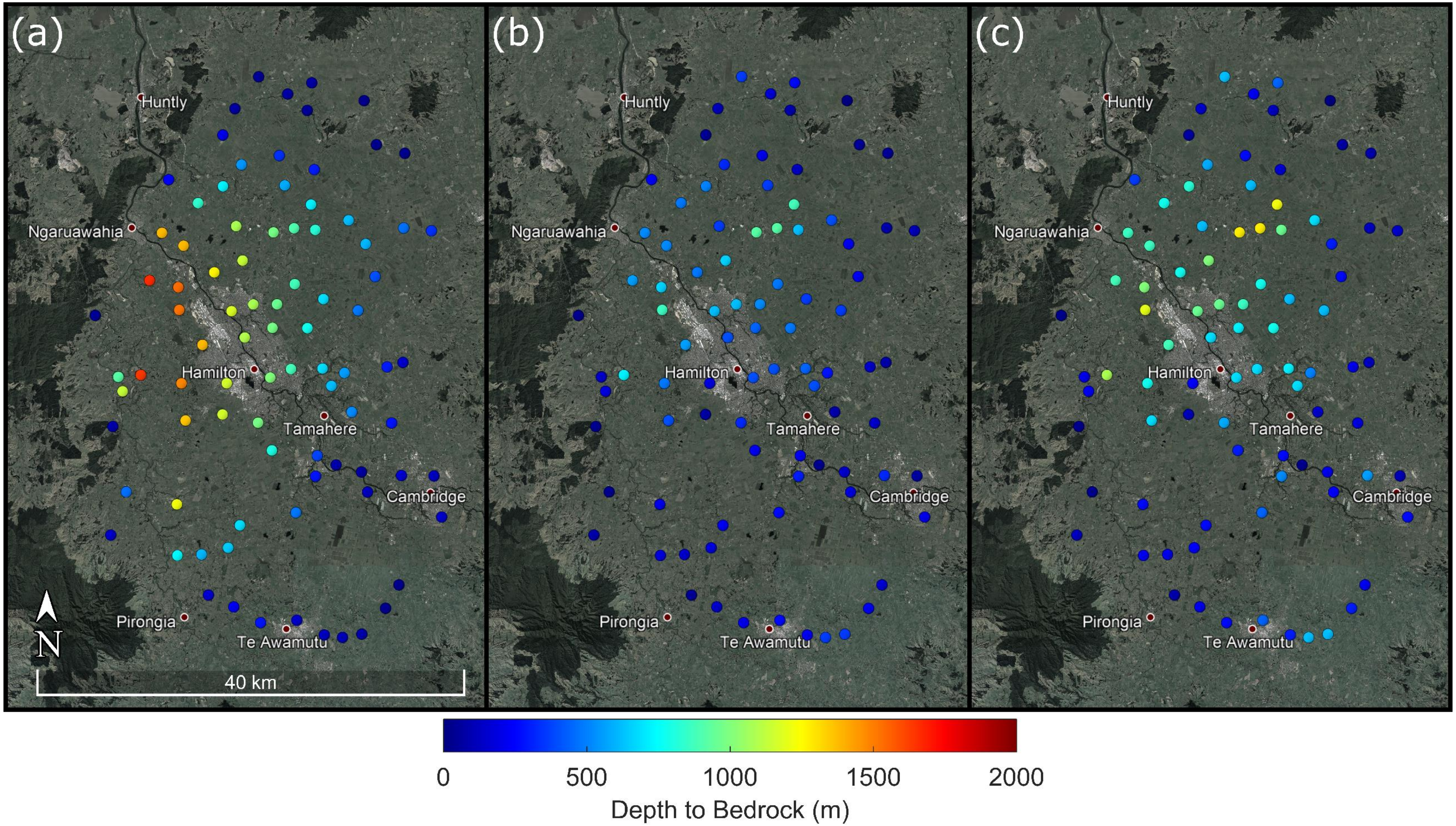

Figure 19. Basin depth characteristics in the Waikato region (a) Type 1 model; (b) Rapid model using the quarter wave length approach; (c) Rapid model using the transfer function approach.

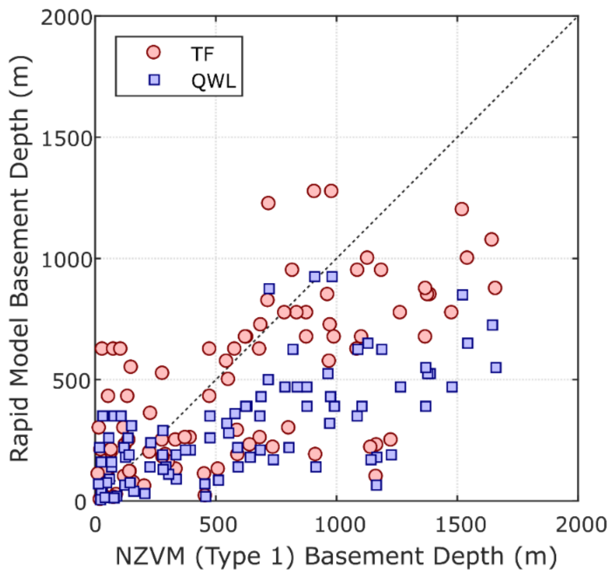

Figure 20. Comparison of Waikato basin depths from rapid method and Type 1 model.

6.5 Canterbury

A Type 4 model for the Canterbury region was developed by Lee et al. (2017) and has continued to be revised iteratively as part of research in the QuakeCoRE Flagship 1 programme. This model was constrained based on a large dataset of seismic reflection lines, petroleum and well logs, and CPT data. The 'rapid' basin model method was compared against this Type 4 3D velocity model for the region.

Site period measurements and representative 1D shear wave velocity profiles have been developed in previous studies (Deschenes et al. 2018, Wotherspoon et al. 2015, 2018). In Canterbury, multiple H/V peaks were present at a number of sites, representative of multiple impedance contrasts in the profile. This analysis focusses on the peaks that are likely most representative of the fundamental site period of the soil profile to bedrock. Two deep shear wave velocity profiles were used to represent the soils in the region and develop the quarter wavelength and transfer function-based D-T_0 relationships (Figure 15c)). One from Lincoln was used to represent locations where interbedded gravel and sediment layers were present, and one from Darfield was used to represent locations inland from this were no interbedding was present. Together, the map of the fundamental site periods and the Canterbury D-T_0 relationships were used to estimate the depth to bedrock in Canterbury.

The variation in the basement depth is similar for all models in Figure 21, with the shallowest regions near the edge of the basin and the Banks Peninsula, then rapidly increasing moving towards the centre of the basin. All models show a slightly shallower basement depth representative of a saddle structure between the Banks Peninsula and the Canterbury foothills north-west of Darfield. Along the edge of the basin the estimated depth are similar for all models, due to the similar D-T_0 relationships in the short site period range. The difference between the two D-T_0 relationships becomes clear in the deepest parts of the sedimentary basin, as a result of the divergence of the two relationships at larger depths. In these areas the transfer function-based depths compare well with the Type 4 model depths, with similar maximum depths of approximately 2000 m. The quarter wavelength-based depths are much shallower, with a maximum depth of approximately 1600 m.

All the basin depth estimates from the Type 4 model and the 'rapid' approaches are compared in Figure 22. This shows that there is a general agreement between the Type 4 and the transfer function depths, with a close scatter of points about the 1:1 line. This agreement is extremely good down to a depth of 1000 m. The quarter wavelength based depths are mostly lower than the Type 4 model, with these points located below the 1:1 line.

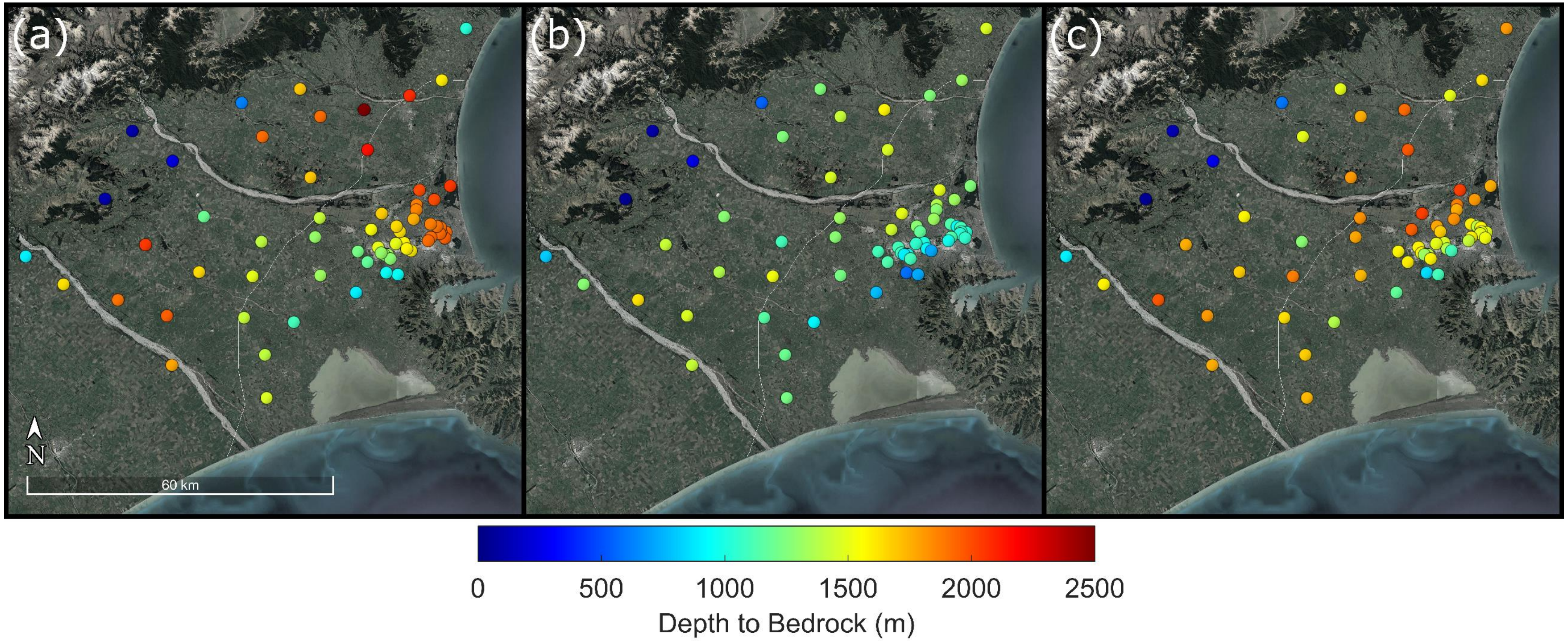

Figure 21. Basin depth characteristics in the Canterbury region (a) Type 4 model; (b) Rapid model using the quarter wave length approach; (c) Rapid model using the transfer function approach.

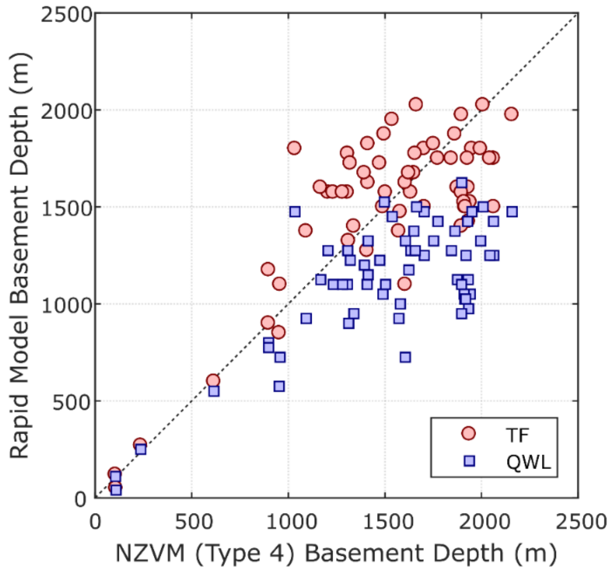

Figure 22. Comparison of Canterbury Basin depths from depths from the rapid method and Type 4 model.

7 Conclusions

This report has presented the development and application of a methodology to provide 'rapid' geophysical characterisation of New Zealand sedimentary basins using the horizontal-to-vertical spectral ratio method and deep shear wave velocity profiles. It has demonstrated the usefulness of the method in providing initial information on basin structure that can be further refined as more data comes available, in particular through the use of a transfer-function based analysis approach.

New deep shear wave velocity profiles and site period estimates in Waikato, Hauraki Plains and Hawke's Bay have provided an improved understanding of the properties of regional soil deposits and the regional variability in dynamic site characteristics. In Waikato fundamental site periods in excess of 5 seconds were recorded, while in the Hauraki Plains site periods were greater than 6 seconds in some areas, suggesting deep basins in both regions.

The 'rapid' method was able to provide initial insight into the structure of the basin under Napier, where basin models have not yet been published. There were clear differences between the Type 1 models and the 'rapid' model in some areas of Waikato and the Hauraki Plains, with the 'rapid' method likely providing a better representation of the basin structure and providing additional insight into the basin structures.

The depth estimates from Type 4 models and the 'rapid' model in Canterbury were in good agreement, with the variation in depth across the region well represented and similar depths estimated throughout. This provided a good demonstration of the effectiveness of the method, particularly given the aim is to provide initial information on basin structure that can be further revised over time.

These 'rapid' models can be used to provide an initial estimate of the potential site effects within each of these basins, feeding into the ground motion simulation research. This will result in better constraint of the seismic hazard on the built environment and the community as a whole. Improved representation of seismic hazard will feed into earthquake engineering practice, both in the assessment of existing infrastructure and design of new infrastructure. The focus on the 'rapid' characterisation in the first instance will allow for earlier dissemination of research outcomes into practice.

Future research will look to expand the application of this method to a wider range of basins across New Zealand. A number of topography based models have been developed for a number of basins already, so these will be a suitable first target for improving the resolution of the basin structure and characterising the shear wave velocity characteristics. As more information is gathered for each basin there can be a progressive improvement in these models, enabling better constraint on potential ground motion amplification effects.

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10 Outputs

10.1 Peer-reviewed publications

Jeong, S. & Wotherspoon, L.M. (2019) Development of a Waikato Basin T0 and depth model by the H/V spectral ratio method, Pacific Conference on Earthquake Engineering, 4-6 April, Auckland, NZ.

Rana, Z. (2020) Dynamic Site Characterisation of the Hauraki Plains, MSc Thesis, University of Auckland.

Stolte, A.C., Wotherspoon, L.M. & Girgis, P. (2020) Dynamic site characterisation of the Hawke's Bay sedimentary basin using H/V and surface wave methods, New Zealand Society for Earthquake Engineering Annual Technical Conference, 22-24 April, Wellington.

10.2 Other publications

Kaiser, A.E., Hill, M.P., Wotherspoon, L.M, Bourguignon, S., Bruce, Z.R., Morgenstern, R. & Giallini, S. (2019) Updated 3D basin model and NZS1170.5 subsoil class and site period maps for the Wellington CBD: Project 2017-GNS-03-NHRP. Lower Hutt (NZ): GNS Science. Consultancy Report 2019/01.