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Dynamic Site Characterisation of the Manukau Lowlands Region of Auckland, New Zealand

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ABSTRACT

This paper presents the characterisation of the shear wave velocity (Vs) of typical deposits in the Manukau Lowland region of Auckland, New Zealand. Auckland is New Zealand's largest city with a population of 1.4 million and has some of the highest land prices in New Zealand. Although it is assumed that Auckland has a low seismic hazard compared to the rest of the country, there is the potential for damaging earthquakes on known or unknown faults. Preliminary investigations have identified peat deposits with thicknesses and Vs well below the limit for site subsoil class E, the softest of the site classes for seismic design in New Zealand. The existence of basaltic deposits over alluvium means that the appropriate site class in these locations depends on the combination of thickness and Vs of these deposits, and the fundamental period of overlying structures.

Introduction

The Canterbury earthquake sequence and the recent Cook Strait earthquake sequence have highlighted the need for detailed research into earthquake induced ground motions in highly populated areas of New Zealand. Auckland is New Zealand's largest city with a population of 1.4 million (Statistics New Zealand 2014) with some of the highest land prices in the country. It has generally been assumed that Auckland has a low seismic hazard because of its tectonic setting away from plate margins and major known fault systems, however there is the potential for a significant earthquake along an unidentified or off-shore fault, as there may also be large faults in close vicinity to the city whose seismic potential are unknown (Kenny 2007). The proximity of Auckland to known active seismic sources (Figure 1a) indicates relatively low risk for large magnitude events. Earthquakes that can cause significant shaking in Auckland are predominantly associated with faults to the east, beneath the Bay of Plenty and East Coast regions. These seismic sources are associated with the Hikurangi Subduction zone and the Taupo Volcanic Zone. Nearby seismic sources that have the potential to cause significant shaking have low activity rates, and thus pose less of a hazard. The likelihood of a large magnitude (resulting in high accelerations) earthquake from a known seismic source close to the city centre (such as the Wairoa North Fault, 60 km away) is low, however there are frequent close, low magnitude earthquakes and distant high magnitude earthquakes that contribute to the seismic hazard in Auckland.

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This paper presents preliminary investigations as part of an ongoing project, with an aim of increasing the understanding of the dynamic site response in the Auckland region through characterisation of the dynamic properties of typical soil profiles in the region. The initial stages of this research involve geotechnical and geophysical field investigations to characterise the shear wave velocity (Vs) of the dominant surficial deposits in the Manukau Lowlands region of Auckland. The revised Auckland Unitary Plan (Auckland Council 2015) is encouraging urban and commercial expansion with a focus on development in the Manukau Lowlands. Given this, there is a real need to better understand the dynamic response of different soil profiles in the region. This paper provides an overview of the typical deposits in this region and the surface wave testing methodology. Subsurface investigation data is used to constrain the layering during the development of the Vs profile at each location. The problematic soils and soil profiles characteristics of the region are then discussed.

Geology of the Manukau Lowlands

Auckland is a region with varying degrees of complexity in the subsurface due in part to the influence of the Auckland Volcanic field on the near surface structure in Auckland. The Manukau Lowlands, in the southern part of Auckland, are an ideal study area due to the diverse range of soil types that exist in this area, including volcanic deposits, soft alluvial and swamp deposits, and reclaimed land. Past geophysical, geotechnical and subsurface investigation methods have provided some indication of the full extent of variability and thicknesses of these deposits in Auckland, however no centralised subsurface model currently exists to provide a clear picture of the region.

Surface deposits have been grouped into categories of relevance for this research in a geological map of the Auckland region summarised in Figure 1a, and a LiDAR based digital elevation model (DEM) of the focus area of the Manukau Lowlands in Figure 1b. Categories of surface deposits have been identified based on geotechnical properties and layering that could have an influence on dynamic site characteristics. The grouped categories were initially derived using layer information from the Auckland QMAP (Edbrooke 2001). However, these were not based solely on geological formations, and separate unit types were delineated using other site investigation data from the region.

The underlying greywacke basement across the region is part of the Waipapa Group, at this unit is shown to outcrop to the east in the Hunua Ranges, as indicated in Figure 1a. Above the basement are the East Coast Bays Formation interbedded sandstone and mudstone deposits which are usually highly weathered near their interface with overlying materials. These materials outcrop in multiple locations across the region, and are highly weathered at the ground surface. Alluvial deposits from the Puketoka Formation are widespread, forming in valleys across the region. In the flat low-lying parts of the region are large swamp deposits and peat bogs. The Auckland volcanic field has greatly contributed to the variability in geotechnical properties observed across the greater Auckland Region. Lava flows from volcanic eruptions in the area have deposited highly variable basaltic deposits over these original strata (Searle and Mayhill 1981; Ballance and Smith 1982), along with ash, lapilli and tuff deposits.

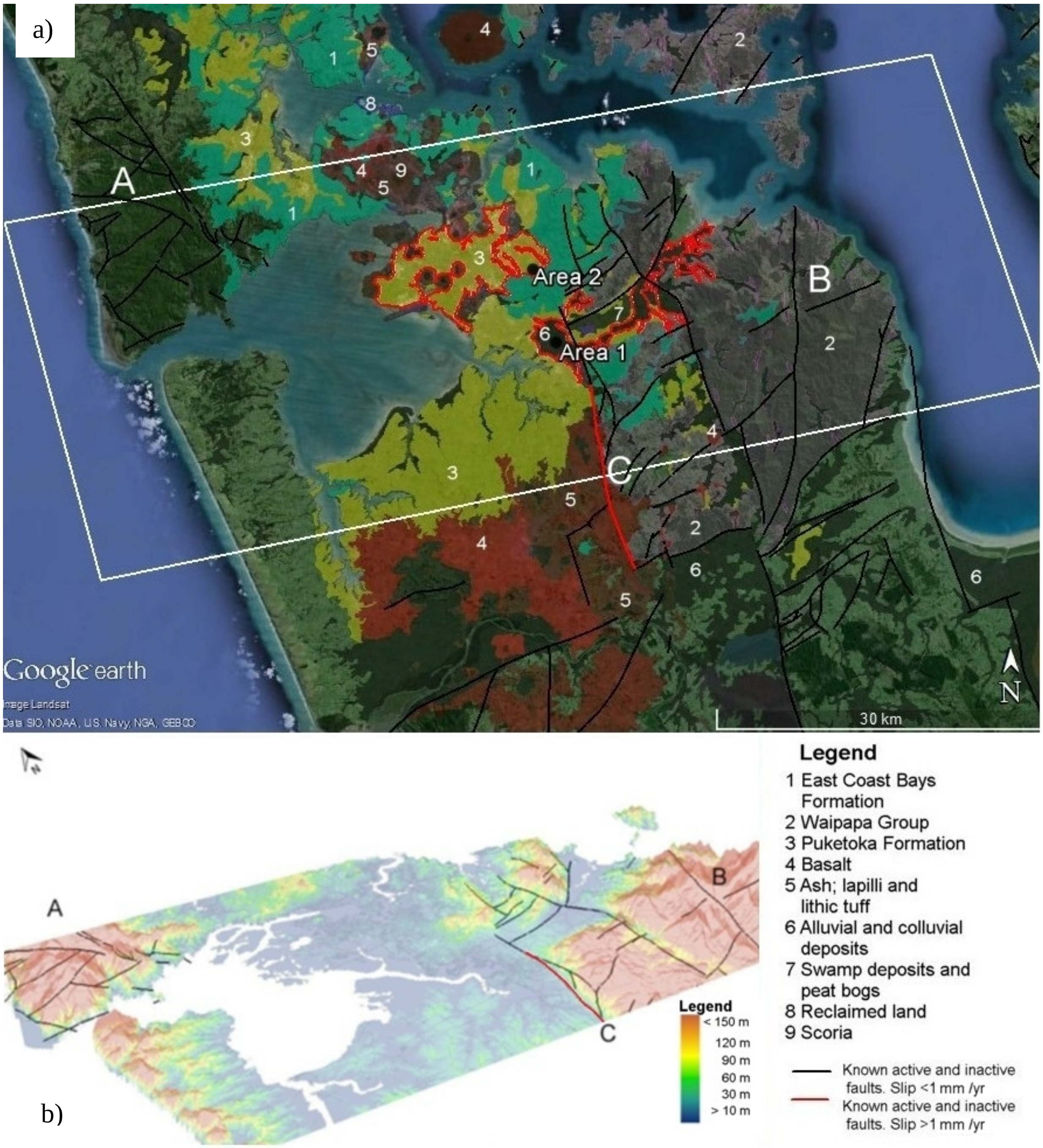

Figure 1 a) Aerial view of the wider Auckland region with mapped surficial deposits, and mapped faults (Edbrooke 2001) relevant to this research (Google Earth Pro 2013). The white box shows the extents of Figure 1b; b) LiDAR DEM, gridded at 1 m showing the extents of the Manukau Lowlands. The Manukau Lowlands can be broadly categorised as the low lying area with an elevation <10 m. On both figures, labels A, B and C, mark the Waitakere Ranges, Hunua Ranges and a segment of the Drury fault, respectively. The black lines show faults (active and inactive) with a slip rate < 1 mm /yr, red lines indicated a slip rate > 1 mm/yr.

Surface wave testing methodology

Active-source surface wave testing approaches were used in the Manukau Lowlands to characterise the properties of different stratigraphic units, and were combined with data from existing intrusive investigations (i.e. boreholes and cone penetration tests). Both Multichannel Analysis of Surface Waves (MASW; Park et al. 1999) and Spectral Analysis of Surface Waves (SASW; Stokoe et al. 1994) approaches were used to analyse the dataset at each site. Both MASW and SASW methods are non-intrusive seismic surveying techniques which characterise the propagation of surface waves generated by an impact source (e.g. hammer or drop weight). Incorporation of both techniques into data analysis allows for greater robustness in the development of the experimental dispersion curve, along with increased confidence in the data.

The surface wave testing used a linear array of 24 4.5 Hz geophones at 2 m spacing. Although different array setups are possible, this choice provided the best option for achieving the required data resolution at the test locations. Multiple offsets source were used for the MASW testing at each site to account for any near source effects or noisy data. A 6 kg sledgehammer and a 90 kg drop weight were used to generate surface waves at each site. Both sources were used with a metal base plate overlain by a rubber mat, which was used to develop energy over a wide range of frequencies. P-wave refraction data were collected where necessary to determine ground water depth, which was used to help constrain the inversion of shear wave velocity profiles. A minimum of five shots were collected at each offset and stacked to improve the signal to noise ratio of the data.

The MASW data was analysed using the frequency domain beamformer method (Zywicki 1999), and the dispersion curve was picked by identifying the maximum spectral peak/peaks in the frequency/wavenumber domain. The SASW data analysis used the phase unwrapping method for data in the frequency range of interest (Cox and Wood 2011). Receiver pair spacings included 1dx, 2dx, 3dx, 4dx, 6dx, 8dx, 10dx and 12dx, where dx is the spacing between each geophone Individual dispersion curves for each of these receiver spacings were combined to develop a composite SASW dispersion curve. Both MASW and SASW dispersion data was then combined to develop a mixed-method composite dispersion curve. The dispersion data was then divided into 30 wavelength bins using a log distribution. The mean phase velocity and associated standard deviation was then calculated for each bin, resulting in an experimental dispersion curve with associated uncertainty.

The dispersion data was inverted using the neighbourhood algorithm approach in Geopsy (Wathelet 2008). The layering used in the inversion was constrained using subsurface investigation data to provide a more realistic representation of the actual shear wave velocity profile. The depth of the shear wave velocity profiles obtained for each site was limited to the maximum experimental wavelength divided by two (i.e., $\lambda_{max}/2$).

Shear wave velocity characteristics

Surface wave testing at a number of locations across the study area have been used to develop representative shear wave velocity values for a range of typical Auckland deposits. This data has been combined with measured shear wave velocity data from other studies (e.g. Wotherspoon and Orense, 2010) and summarised in Table 1. The location of the two study areas in the Manukau Lowlands are indicated in Figure 1. The surficial deposit at Area 1 (Figure 1a) is identified as silt underlain by unclassified Tauranga Group alluvium. Subsurface investigation data showed that the silt deposit has a high organic content ranging from 40% to 60%. The surficial deposit at Area 2 (Figure 1a) is identified as the Puketoka Formation alluvium.

The depositional environment of the strata in Area 1 (Figure 1a) has led to variability in the thickness in the surficial peaty silt unit, with the depth of this deposit ranging from 5 m to 20 m across the Manukau Lowlands. At the testing location, subsurface investigations indicated that the peaty silts extended to a depth of 10.5 m, with Vs increasing from 65 m/s to 90 m/s within this depth range. The unclassified alluvial materials below this also had a low Vs, with the shear wave velocities measured between 10 m and 20 m depth.

The Puketoka Formation surficial deposits in Area 2 (Figure 1a) were deposited in a marine environment, and are comprised of a wide variety of materials. At this location there is an increase in the Vs from 150 m/s – 300 m/s from the surface down to the more competent material at a depth of 9 m. In the Manukau Lowlands the unit generally consists of silts and clays with variable sand content (Kear 1961). Below this the highly weathered East Coast Bays Formation has a Vs of 400 m/s -500 m/s. This is representative of much of the highly weathered East Coast Bays Formation across the region, with Vs increasing as the degree of weathering reduces.

Volcanic deposits have not only created a range of complex geotechnical profiles across Auckland, there is also considerable variability within the deposits themselves. In many locations subsurface investigations have shown that these deposits can be affected by weathering, they can be highly fractured, and there are locations that are highly vesicular. These factors all contribute to the significant range in Vs measured in these deposits outlined in Table 1, and in site characterisation for seismic design the average representative properties are most appropriate.

Table 1. Range of measured shear wave velocities for typical deposits in the Manukau Lowlands

Deposit	Shear wave velocity (m/s)
Peaty silt	65 - 90
Tauranga Group Alluvium	115 -130
Puketoka Formation	150 - 300
Highly weathered ECBF	400 - 500
Basalt	900 - 2000

Current design standards and shear wave velocity

The New Zealand Standard for Structural Design Actions (NZS1170.5; Standards New Zealand 2004) summarises site subsoil classes (referred to as site classes herein) for seismic design in New Zealand. Table 2 provides an overview of site classes A-E according to Vs and site period, where A is strong rock, B is rock, C is shallow soil, D is deep or soft soil, and E is very soft soil.

Table 2. Summary of site class classification using shear wave velocity or site period as defined by NZS1170.5:2004.

Site Class	Type	Classification criteria
A	Strong to extremely-strong rock	Shear wave velocity of 1500 m/s or more over 30 m Not underlain by materials with a shear wave velocity less than 600 m/s.
B	Rock with no more than 3 m depth of highly to completely weathered material on the surface:	Shear wave velocity of 360 m/s or more over 30 m Not underlain by materials having a shear-wave velocity less than 300 m/s High compressive strength, in the region of between 1 and 50MPa
C	Shallow Soil Sites that are not Class A, B or E sites	Low amplitude natural (fundamental) period (Tn) is less than or equal to 0.6 s
D	Shallow Soil Sites that are not Class A, B or E sites	The low amplitude natural (fundamental) period (Tn) is greater than 0.6 s
E	Very Soft Soil Sites	More than 10 m depth of soils with shear wave velocities of 150 m/s or less

The stratigraphy in Auckland is very complex in many locations, and does not easily fit into the NZS1170.5 site classification framework (Table 2). The New Zealand standards will often classify basalt at the surface as a Class B rock site (Standards New Zealand 2004), especially if subsurface investigations are not sufficient to identify underlying alluvial material between the surface basaltic material and the underlying East Coast Bays Formation sandstone and mudstone. Volcanic geological material will have a great influence and be the prevailing 'stiff' near surface material across Auckland. Given the variability of Vs within the basalt deposits themselves, crosshole or surface wave testing are probably the most appropriate methods for site classification as they can define representative properties across the variable deposits. Robust characterisation of volcanic units is necessary for defining the variability in the stiff overlying units. The effect of the 'stiff over soft' layering, where basalts have been deposited over alluvium and unwelded tuff deposits, will have the largest influence in dynamic response characteristics at these sites, even if these materials have Vs greater than the 300 m/s limit set for underlying materials as summarised in Table 2. Analysis has shown that this 'stiff over soft' characteristic has a significant effect on response spectra. The combination of layer thickness and Vs of the volcanic and alluvial deposits means that depending on the fundamental period of the overlying structure at 'stiff over soft' sites, different site classes may be appropriate at a particular location. It is the combination of these factors that will determine whether site class B or C is appropriate.

Shear wave velocities at Area 1 show that the surface peaty silt deposits, which extend to 10.5 m corresponds to site class E according to NZS1170.5. These deposits have a thickness greater than the site class E limit of 10 m, and Vs significantly below the site class E limit of 150 m/s. If the underlying soft alluvium is also taken into account at this site, the shear wave velocity for the top 20 m is well below the site class E limits (Table 2) in both shear wave velocity and thickness. These deposits are likely to be exhibit strong amplification of ground motions from the underlying rock to the ground surface and may not be adequately captured by the NZS1170.5 framework as their properties are so far below the site class E shear wave velocity limit. Even at locations with a 5 m thickness of these deposits, the site response characteristics would be similar to the site class E limiting criteria (i.e. 5 m of 75 m/s may be similar to 10 m of 150 m/s in terms of nonlinear site response). Additional investigations are needed to assess the amplification that will develop in these deposits.

Conclusions

The variability of subsurface deposits in the Manukau Lowlands and the greater Auckland Region, will have an effect on dynamic site characteristics which are not accounted for in existing New Zealand Standards for seismic design. The full extent that subsurface geological variability in the Manukau Lowlands has on shear wave velocity of sites is not yet fully known and further testing is necessary. However, indicative testing has highlighted the difficult soils and complex soil profiles that exist in the region. The softer peat material at Greenfield sites has been shown to have shear wave velocities and thicknesses significantly below the site class E limit in some areas. Amplification effects at these sites could have implications on the design of both residential and commercial structures. Basalt deposits will have a great influence and be the prevailing ‘stiff’ near surface material across much of Auckland, and the variability within the stiff overlying structure itself is likely to contribute to changes in dynamic response characteristics. The fundamental period of the overlying structure at these locations, and the combination of the thickness and Vs of the volcanic and underlying alluvial deposits with define which site class is appropriate.

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