Wellington basin amplification: research goals and update from the NSHM programme

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ABSTRACT

In Wellington, 3D basin amplification effects observed at 1 – 2 second spectral periods were identified as one factor likely to have exacerbated damage to mid-rise structures during the 2016 Mw 7.8 Kaikōura earthquake (Bradley et al. 2018; MBIE, 2017). These local basin-specific ground-motion effects are not typically fully captured in traditional seismic hazard models.

A component of the newly launched National Seismic Hazard Model (NSHM) programme aims to quantify spatial patterns and event-to-event variability of ground-motion amplification effects in central Wellington. This project will investigate the advances provided by both new empirical ground motion models available since the previous NSHM (Stirling et al. 2012) and also by physics-based ground motion simulation methods. The geometry and sediment fill of the Wellington basin under Wellington's CBD is relatively well-characterised (Kaiser et al. 2019; 2020), allowing a detailed case study to be undertaken. We will ultimately provide a summary of the state-of-knowledge of Wellington basin amplification effects and an initial roadmap towards capturing these effects in seismic hazard nationwide.

Here we present an introduction to the NSHM Wellington basin project and its goals. We also outline first steps focused on the compilation of a new central Wellington Vs30 map, a regional basin velocity model and a Hikurangi earthquake ground-motion simulation framework.

1 INTRODUCTION

1.1 Basin amplification effects

Many New Zealand (NZ) urban centres are situated on sedimentary basins containing softer material within which seismic waves can become trapped and amplified. In Wellington, these basin amplification effects were clearly observed in the 2016 Kaikōura earthquake and 2013 Cook Strait earthquakes (Bradley et al. 2018; Holden et al. 2013), expressed at 1 – 2 s spectral periods in much of the CBD. For the Kaikōura earthquake, in particular, the large Mw 7.8 source generated significant energy in this period range, which coupled with amplification by the Wellington basin, led to appreciable amplitudes and significant damage concentrated in mid-rise structures likely to have corresponding fundamental periods.

The consistency of these amplifications at the low to moderate levels of shaking previously observed in Wellington indicates they will also occur in future events. However, no measurements of strong shaking (>0.3 g) exist in the historical record, such that the nature of amplification in very large events that dominate the hazard in Wellington (e.g. Hikurangi subduction zone and Wellington Fault events) remains a source of investigation.

1.2 Treatment of amplification effects in NSHM models

The specific character of basin amplification effects will depend on the particular basin of interest, making them challenging to fully capture within traditional seismic hazard models. The previous versions of the New Zealand NSHM (Stirling et al. 2012) used the empirical ground-motion model of McVerry et al. (2006) and its amplification model based on NZS1170.5 site subsoil class (Standards NZ 2004). This model was derived using NZ historical seismic data and knowledge of NZ site conditions available at that time, but still makes only broadly averaged approximations of amplification effects. As a result, two NZS1170.5 subsoil class D sites (Deep or Soft Soil) in different sedimentary basins are treated the same, although they may exhibit significantly different amplification character.

Newer ground-motion models (e.g. NGA-West2 models; Gregor et al. 2014) will be incorporated into the NSHM revision currently underway (Gerstenberger et al. 2020), and are based on much larger global ground-motion databases and alternative continuous site parameters e.g. Vs30, Z1.0, Z2.5 (Ancheta et al. 2014; Vs30=time-averaged shear-wave velocity in the uppermost 30m; Z1.0 [Z2.5] = depth to material of shear-wave velocity 1km/s [2.5km/s] or greater). These models can be applied anywhere in NZ, but continue to treat site response in an ergodic fashion, i.e. they represent global averages for a given site condition. The application of new ground motion models to NZ will be studied in detail within the NSHM programme and inform the development of a new ground motion modelling framework. This work will also inform future discussion and development of the uptake of the NSHM into NZ's design codes, including the treatment of site classification. Once established, the new NSHM national ground-motion modelling framework will also be applied in central Wellington to investigate its ability to capture Wellington basin amplification effects relative to previous models.

Physics-based ground motion simulations provide additional avenue to model basin amplification effects, allowing complex 3D wave propagation to be captured for a specific basin. The quantification of uncertainty of such methods is an outstanding challenge, however significant progress in recent years has been made (e.g. Bielak et al. 2010; Chaliub et al. 2010; Dreger et al. 2015; Bradley et al. 2017; Lee et al. 2020). These models are likely to increasingly contribute to next-generation seismic hazard models by providing information where empirical data is sparse (e.g. large magnitude earthquakes at near-source distances).

Long-period basin-specific amplification that has been well-characterised has begun to be considered in some national or regional hazard mapping efforts (e.g. US hazard maps presented in Shumway et al. 2010). The treatment of intermediate (or short) period basin-specific effects common in many NZ basins, presents an additional modelling challenge, due to factors such as (i) the shorter spatial scale of amplification effects (shorter wavelength of amplified seismic waves) and (ii) the potential for soil nonlinear effects that become increasingly important at strong shaking and shorter periods. Progress can be made through detailed characterisation of the 3D subsurface coupled with investigation of empirical and physics-based ground motion modelling and consideration of uncertainty.

1.3 NSHM current revision: Wellington basin goals

Our goals under the NSHM programme (Gerstenberger et al. 2020) are to use an investigation of Wellington basin amplification as a case study to advance state-of-the-art treatment of basin amplification effects in seismic hazard. Although the focus will be on Wellington, we also intend to apply the findings and those available from other regions and studies to develop an initial roadmap for future consideration of amplification effects nationwide. Our specific aims are to:

- provide a new Wellington CBD Vs30 map, which will be a significant update of that of Semmens et al. (2010). The Vs30 map will be a necessary input the application of empirical- and physics-based ground-motion models on an urban scale for this project. It will also serve as a guide for the engineering sector on the available Vs30 information in Wellington. This will expand on the database of geotechnical site data that was used to compile the updated CBD site period and subsoil class maps of Kaiser et al. 2019.
- provide a new region-wide 3D Wellington basin velocity model, drawing together previous modelling work of Kaiser et al. (2019), Hill et al. (in prep); Benites et al. (2005), Boon et al. (2010). This model is necessary for the physics-based ground motion simulations.
- simulate ground motions in the Wellington region from large earthquakes that dominate the hazard in Wellington and will result in strong shaking, e.g. Hikurangi subduction zone and Wellington Fault earthquakes (method of Bradley et al. 2020, Graves and Pitarka 2010; Roten et al. 2020)
- apply new NSHM ground motion modelling framework (see Section 1.2) in spatial detail to central Wellington
- quantify amplification from empirical and physics-based ground-motion models relative to each other and previous NSHM models
- explore what strategies / framework could be applied to capture amplification within New Zealand basins in the future.

2 CENTRAL WELLINGTON VS30 MAP

The first step of goals outlined above is to provide a new Vs30 map of central Wellington. This map is necessary as input into both the Wellington application of the NSHM empirical ground-motion modelling framework as well as the physics-based simulations. The previous Vs30 map of Semmens et al. (2010) was drawn based only on sparse data points; the available shear-wave velocity (Vs) data has since significantly expanded allowing more robust and detailed estimates of Vs30 in central Wellington. The final Vs30 map when produced will serve as both a summary and guide to the available data in Wellington.

2.1 Vs30 database and model

To date, we have compiled a database of more than 100 Vs30 measurements (Figure 1, working version). Each Vs30 estimate is assigned a provision quality estimate (Q1 = well-constrained; Q2 = reasonably constrained; Q3 = poorly constrained) based on the quality descriptors of Kaiser et al. (2017). The highest quality estimates in the database (Q1, Q2) are derived from measured downhole Vs profiles (triangles) and passive surface wave methods (e.g. MASW, ReMi or SPAC; circles).

In addition, we have supplemented our Vs30 database with estimates derived from the current working version of our 3D velocity model for central Wellington (Kaiser et al. 2019; Hill et al. in prep.; Figure 2). These estimates are extracted at locations where borehole data is available down to depths that reach the base of the soft/loose deposits; Vs30 is then calculated using the T0 calculation method, i.e. assuming a four-way-travel-time approximation and an average assigned velocity for each near-surface layer (dots in Figure 1). The near-surface 3D velocity block model used to calculate 'modelled' Vs30 is also shown in Figure 2.

2.2 Preliminary observations

In general, a significant range of Vs30 values are observed across central Wellington reflecting the varying thickness and stiffness of near-surface sediment deposits. As expected Vs30 values are lowest in the areas of fill, but these low values also extend into the Thorndon Basin and are also noticeably low within the Te Aro Basin (correlating with areas of softer near-surface deposits). The 3D near-surface velocity model estimates and measured Vs30 estimates generally match well. However, it is evident from Figure 1 that the near-surface 3D velocity model does not yet fully capture the softness of sediment in parts of Thorndon or around the Basin Reserve, which serves as the basis for further investigation and a velocity model revision.

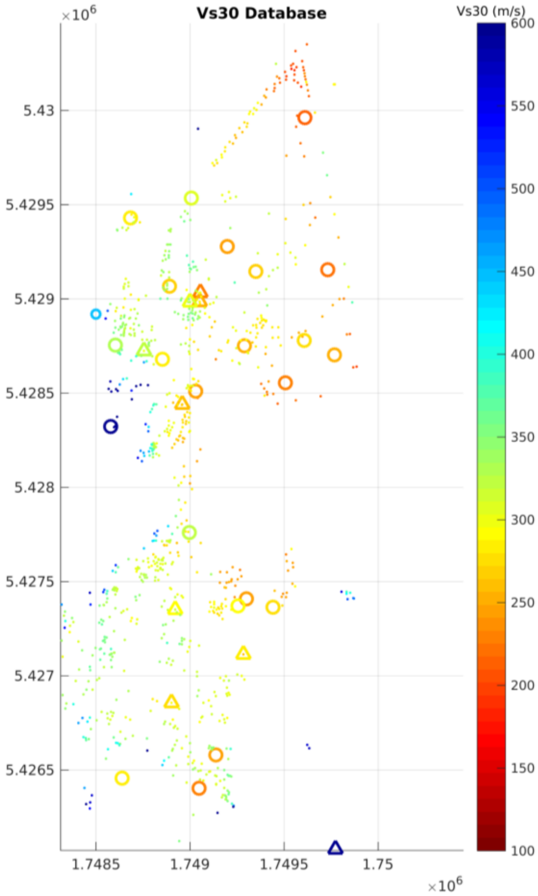

Figure 1: Database of Vs30 measurements in central Wellington to date. Circles indicate measurements derived from non-invasive surface-wave based methods (MASW, ReMi, SPAC), triangles indicate measurements derived from down-hole Vs investigations, and dots indicate measurements calculated using the near-surface 3D velocity model in Figure 4 at locations where boreholes are drilled down to dense deposits (such that the near-sruface structure is well-constrained).

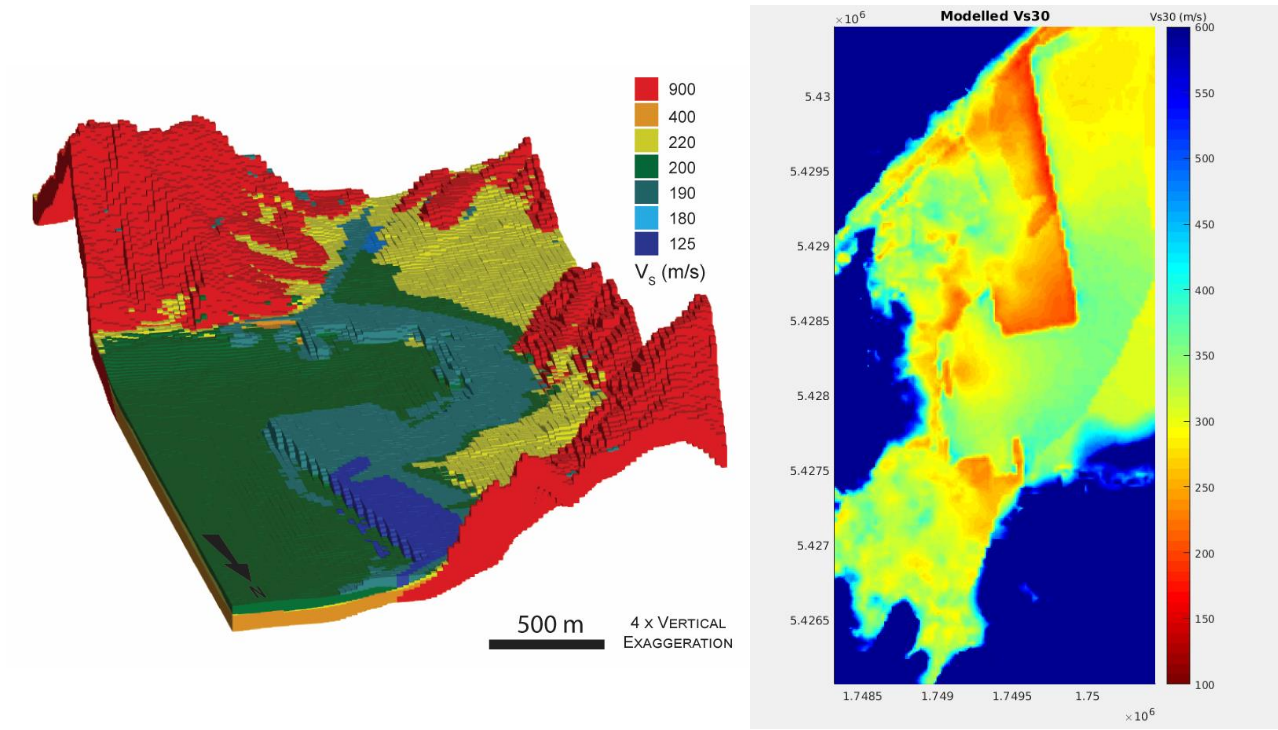

Figure 2: Left: Shear-wave velocity block model for the uppermost 30m in central Wellington. This model utilises an extensive borehole database drawing on that of Kaiser et al. (2019), Hill et al. in prep. and the velocity characterisation based on Semmens et al. (2010). The velocity model will be used to interpolate and guide the Vs30 mapping. Right: A working version of the Vs30 derived from the 3D model, from which data points were extracted in Figure 1; note this map is derived from the 3D model only and not measured data; it is not intended as a replacement Vs30 map.

3 REGIONAL WELLINGTON VELOCITY MODEL

Work has started compiling a regional Wellington velocity model that encompasses the wider harbour area (see Figure 3a). This work extends the central Wellington model of Kaiser et al. (2019), linking it in a consistent way with other 3D models in the wider harbour area (Boon et al. 2010; Benites et al. 2005; Hill & Kaiser 2019, and other unpublished models). The regional velocity model will enable us to simulate ground motion in greater spatial detail than previously possible (Benites et al. 2005; Thomson et al. 2020), exploring complex 3D wave propagation effects as waves enter the basin, becoming trapped and amplified within the soft sediments and interacting with the also steep-sided basin edges.

A critical boundary in our 3D model is the greywacke – sediment interface (see Figure 3b), representing a significant impedance contrast at depth below Wellington. A review of available marine seismic reflection data in the harbour will serve to aid identification of other horizons above the basement interface exhibiting strong impedance contrasts that may be important for our modelling. The existing harbour velocity model adopted for Wellington Fault ground motion simulations by Benites et al. (2005) based on seismic and gravity data will serve as the starting point for the revision. Existing models of the Lower Hutt and Upper Hutt basins as well as the wider Wellington area (Figure 3a) will also be combined together for the simulation runs; this will ensure the simulations and underpinning velocity model can be validated against a suite of observational data from GeoNet strong motion observational sites across the region.

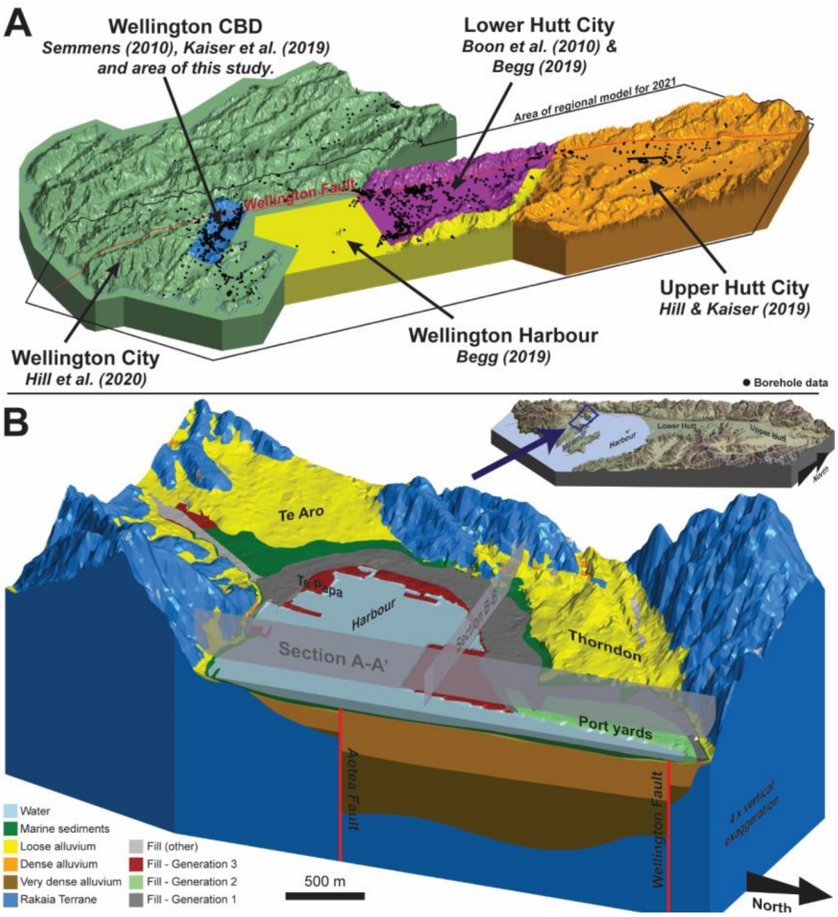

Figure 3: 3D geological models in the Wellington region. A) Extent of proposed 3D regional velocity model (black line) and existing 3D geological models. B) Detailed section of the central Wellington component illustrating the shallow basin and sedimentary structure. A region-wide velocity model will be constructed from these composite models and is necessary to model wave propagation through the wider basin structure; it also allows for validation of the simulated ground motions at GeoNet observations sites across the region.

4 SIMULATION-BASED PREDICTION OF GROUND MOTION FOR WELLINGTON AND MAJOR SUBDUCTION ZONE EARTHQUAKES

Ground motions simulations are underway that propagate seismic waves from a Hikurangi subduction zone earthquake source through a 3D New Zealand velocity model and preliminary Wellington basin velocity model. To gain a robust understanding of mean expected ground motion amplification and its uncertainty, uncertainties in the definition of the kinematic earthquake source as well as the velocity model will be explored.

To explore source uncertainty, an ensemble of potential ruptures derived from a range of kinematic earthquake source definitions are constructed. The resulting simulated ground motions can then be considered as ‘synthetic data’, compared with empirical predictions, and used to update such empirical predictions where they are deemed inadequately constrained. These synthetic data can help fill a gap in empirical ground-motion databases for very large earthquakes at near source distances (no such large subduction zone earthquakes have yet been recorded in New Zealand). Figure 4 provides an illustration of the simulated ground velocity for a potential M8.6 megathrust earthquake on the Hikurangi subduction interface.

Figure 5 illustrates an example of the simulated ground-motion amplification in the central Wellington region as a result of the modelled sedimentary basin and near-surface soil conditions. Simulations of historical events are also being used in order to scrutinize the validity of simulations against observed ground motions, and iteratively improve aspects of the model (e.g., the sedimentary basin) within the constraints of geological, geophysical and geotechnical data.

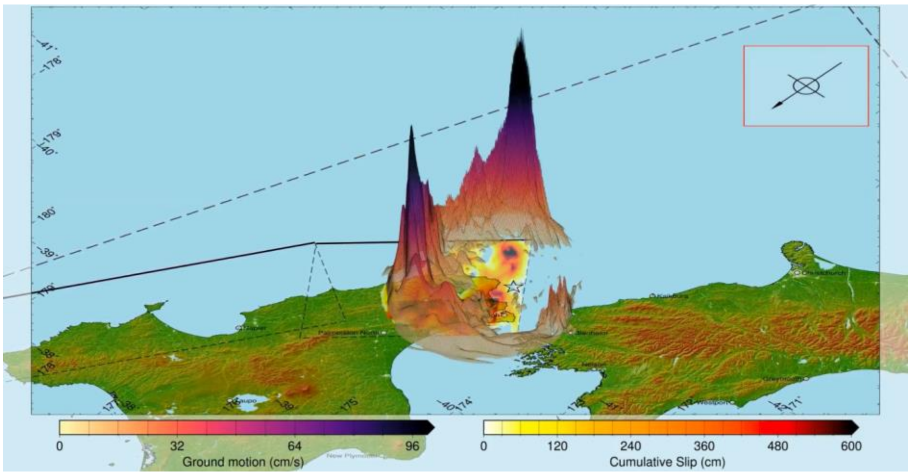

Figure 1: Ground motion simulation of a potential M8.6 earthquake on the Hikurangi megathrust (interface) at time = 39 seconds. The simulated ground motions provide an alternative to the use of empirical ground-motion models that are poorly constrained for such large magnitude events at small source-to-site distances. The full simulation animation can be viewed at: https://www.youtube.com/watch?v=55RhqF7xc78

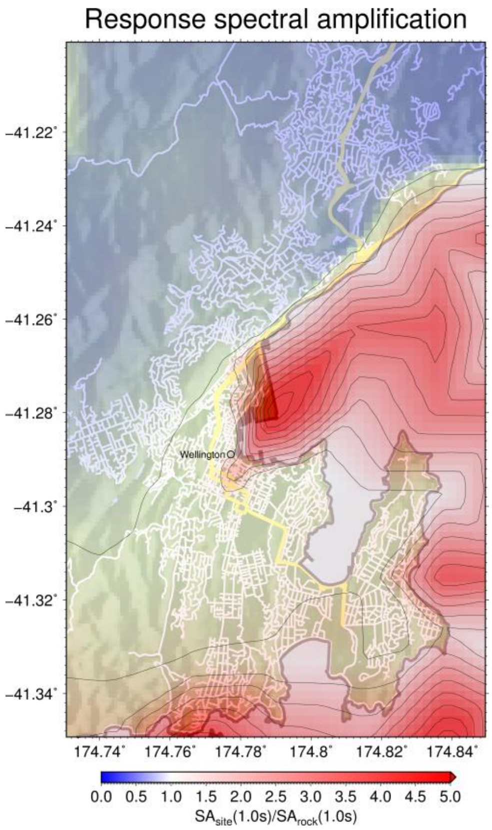

Figure 2: Simulated SA(1.0s) ground-motion amplification (ratio of site ground motion to reference rock conditions) in central Wellington. Amplifications greater than one are observed in the Thorndon and Te Aro Basins, and increase approximately as a function of the distance from the basin edge – particularly with respect to the Wellington-fault bounded Thorndon Basin.

5 CONCLUSIONS

Basin amplification effects can be expected in many urban centres in New Zealand that lie on sedimentary basins, and have been recognised as a factor that exacerbated damage during the Kaikōura earthquake in Wellington. The inclusion of such basin-specific amplification effects in seismic hazard models is recognised as a significant global scientific challenge.

A component of the recently launched NSHM programme aims to progress the quantification of spatially variable amplification effects and their uncertainty in Wellington and use this case study to provide an initial roadmap towards capturing these effects in seismic hazard nationwide. Our first step is to construct an updated Vs30 map of central Wellington; a database of over 100 Vs30 point estimates has now been compiled. We have also begun work on a regional Wellington velocity model and ground-motion simulations of large Hikurangi subduction earthquakes. These first steps will provide the pathway for application and investigation of empirical and physics-based ground-motion modelling methods in central Wellington.

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