Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 50, No. 2, June 2017

GROUND MOTION AND SITE EFFECT OBSERVATIONS IN THE WELLINGTON REGION FROM THE 2016 M_W7.8 KAIKŌURA, NEW ZEALAND EARTHQUAKE

Brendon A. Bradley[1,2], Liam M. Wotherspoon[3] and Anna E. Kaiser[4]

(Submitted *March 2017*; Reviewed *April 2017*; Accepted *May 2017*)

ABSTRACT

This paper presents ground motion and site effect observations in the greater Wellington region from the 14 November 2016 M_w7.8 Kaikōura earthquake. The region was the principal urban area to be affected by the earthquake-induced ground motions from this event. Despite being approximately 60km from the northern extent of the causative earthquake rupture, the ground motions in Wellington exhibited long period (specifically $T = 1 - 3s$) ground motion amplitudes that were similar to, and in some locations exceeded, the current 500 year return period design ground motion levels. Several ground motion observations on rock provide significant constraint to understand the role of surficial site effects in the recorded ground motions. The largest long period ground motions were observed in the Thorndon and Te Aro basins in Wellington City, inferred as a result of 1D impedance contrasts and also basin-edge-generated waves. Observed site amplifications, based on response spectral ratios with reference rock sites, are seen to significantly exceed the site class factors in NZS1170.5:2004 for site class C, D, and E sites at approximately T=0.3-3.0s. The 5-95% Significant Duration, D_{s595}, of ground motions was on the order of 30 seconds, consistent with empirical models for this earthquake magnitude and source-to-site distance. Such durations are slightly longer than the corresponding $D_{s595} = 10$s and 25s in central Christchurch during the 22 February 2011 M_w6.2 and 4 September 2010 M_w7.1 earthquakes, but significantly shorter than what might be expected for large subduction zone earthquakes that pose a hazard to the region. In summary, the observations highlight the need to better understand and quantify basin and near-surface site response effects through more comprehensive models, and better account for such effects through site amplification factors in design standards.

INTRODUCTION

On 14 November 2016 at 12:02 AM local time, the M_w7.8 ‘Kaikōura’ earthquake occurred along the east coast of the upper South Island, New Zealand [1–3]. While the epicentral location of the event was in a largely rural area of New Zealand, the urban Wellington region’s location only 60km to the north of the northern-most causative faults [4, 5] resulted in (on average) moderate ground motions, that in some locations and vibration periods, exceeded the current 500 year return period design ground motion levels [3, 6]. As a result of the shaking intensity and spatial distribution, relatively significant damage occurred to numerous structures in Wellington [7, 8]. One structure had a partial collapse of precast floor units and was the subject of an government investigation [9, 10], while another three structures underwent rapid demolition as a result of earthquake damage [11–13]. As at 7 December 2016, 11% of Wellington office space was reported as closed due to damage [11].

This paper presents salient features of the observed ground motions in the Wellington region in an effort to provide insight into both the characteristics and spatial distribution of the intensity of shaking (for understanding the propensity for damage), as well as to scrutinise the consideration of seismic site effects in the New Zealand loadings standard. Chandramohan et al. [14] provide an overview of the building response in the Wellington region based on building instrumentation observations.

SPATIAL DISTRIBUTION OF GROUND MOTION OBSERVATIONS IN THE WELLINGTON REGION

Figure 1 illustrates the spatial distribution of peak horizontal and vertical ground motions observed in the central Wellington and Lower Hutt regions during the Kaikōura earthquake. The horizontal peak ground accelerations (PGA) are the geometric mean of the two components. The peak horizontal accelerations range from 0.07-0.24g, while the peak vertical accelerations ranged from 0.04-0.10g. The reasons for these large ranges are discussed further in subsequent sections.

The short-period ground motion amplitudes summarised in Figure 1 would be considered as moderate, and hence it is not surprising that liquefaction of native soils, or damage to short period structures, was not prevalent in the region. The moderate PGA amplitudes are the result of the relatively large source-to-site distance (approximately 60km) that Wellington is located from the source, combined with the significant attenuation of short period ground motion intensity over such distances [6]. Because long period ground motion intensity does not attenuate as rapidly with distance, long period amplitudes were significantly larger relative to those at short periods. Figure 2a and b illustrate the ratio of $SA(T = 0.3s)$ and $SA(T = 1.5s)$ (representing short

[1] *Corresponding Author. Professor, Department of Civil and Natural Resources Engineering, University of Canterbury, New Zealand, brendon.bradley@canterbury.ac.nz*
[2] *UPS Visiting Professor, Stanford University, CA*
[3] *Senior Lecturer, Department of Civil and Environmental Engineering, University of Auckland, New Zealand*
[4] *Seismologist, Tectonophysics Department, GNS Science, Avalon, New Zealand*

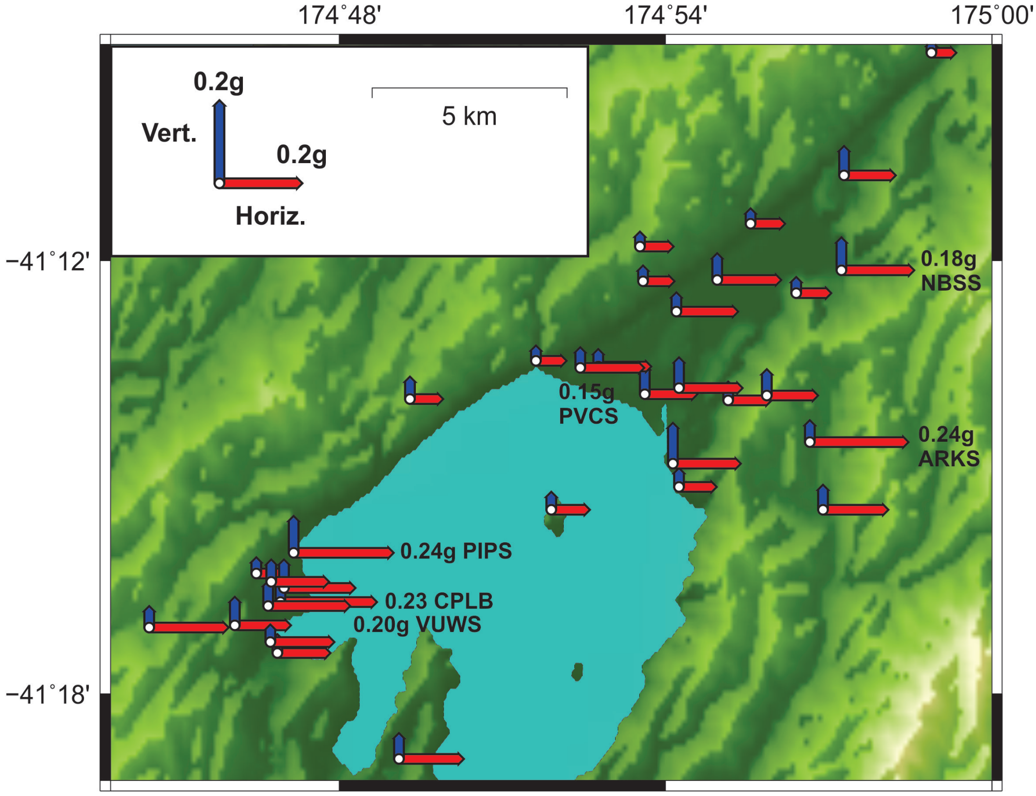


Figure 1: Horizontal and vertical peak ground accelerations observed at GeoNet strong motion stations in Wellington [15].

and longer periods, respectively), with the 500-year return period spectral ordinates from NZS1170.5:2004 (which is the ultimate limit state (ULS) for importance level 2 structures). At short periods the $SA(T = 0.3s)$ amplitudes are on the order of 20-50% of ULS, while the $SA(T = 1.5s)$ amplitudes vary significantly, with a handful exceeding 100% of the ULS demand.

GENERAL GEOTECHNICAL AND GEOLOGICAL CONDITIONS

The Wellington region is one of complex geological and geotechnical conditions as a result of the myriad of active tectonic and geomorphological processes at work. Here we provide a summary of existing information in the central Wellington region, while Boon et al. [17] provide a summary of conditions in the Hutt Valley.

Figure 3a illustrates the geological map of the central Wellington region from Semmens et al. [18]. Semmens et al. [18] provide further details of geotechnical characterisation (i.e. site class, site period, basement depth, V_{s30}), while Kaiser et al. [16] provide estimates of site period and associated uncertainty at strong motion stations. As shown in Figure 3a, the region comprises bedrock, Pleistocene and Holocene alluvial deposits, swamp and marine sediments, colluvial deposits, and staged reclamation using both hydraulic and quarry fill.

For the purposes of understanding seismic site response, the surficial geology map of Semmens et al. [19] lacks sufficient detail. For example, significant differences in weathering within mapped geological units exist, as indicated by greywacke bedrock (sandstone, mudstone) being assigned shear wave velocities in the range of V_s=200-2000m/s. It should be also noted that because the Wellington Fault leads to uplift of the Western hills relative to central Wellington, then for a given depth below sea level, material on the western side of the Wellington Fault is older than its counterpart on the eastern side, and also has been uplifted from greater depths (meaning less weathering). As a result, it can be expected that there is a velocity contrast across the Wellington fault trace in the rock itself. The implications of this logic are further exacerbated by the fact that the region to the east of the Wellington Fault trace in central Wellington is crossed by numerous faults [20], which will have led to greater fracturing of the bedrock in this region, and thus lower seismic velocities.

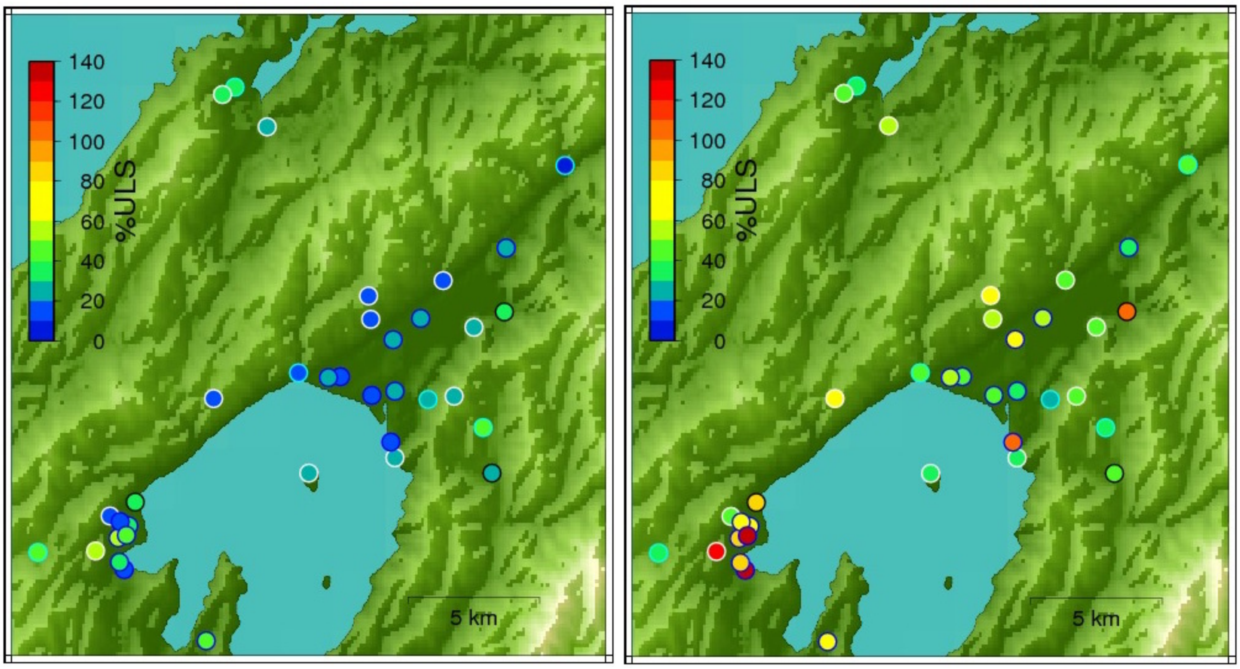
The present understanding of the geological and geotechnical conditions [16, 18, 21] in Wellington is insightful for interpreting the observed ground motions. However, clearly more detailed characterisation of the soil conditions in the central Wellington region is needed to better understand the ground motion observations (discussed in the subsequent sections) and hazard posed from future events. In particular, a greater number of CPT and multi-layered Vs measurements is needed (the predominant SPT-based data have significantly greater uncertainties for soil characterisation); and CPTs that can penetrate surficial gravel lenses to ensure that depths to rock are correctly inferred will significantly improve regional understanding of site effects. Figure 3b illustrates the location of several additional measurements of site period that have been collected since the Kaikōura earthquake as part of ongoing efforts to improve the characterisation in the region.

OBSERVATIONS OF LOCAL SITE AMPLIFICATION

Central Wellington City

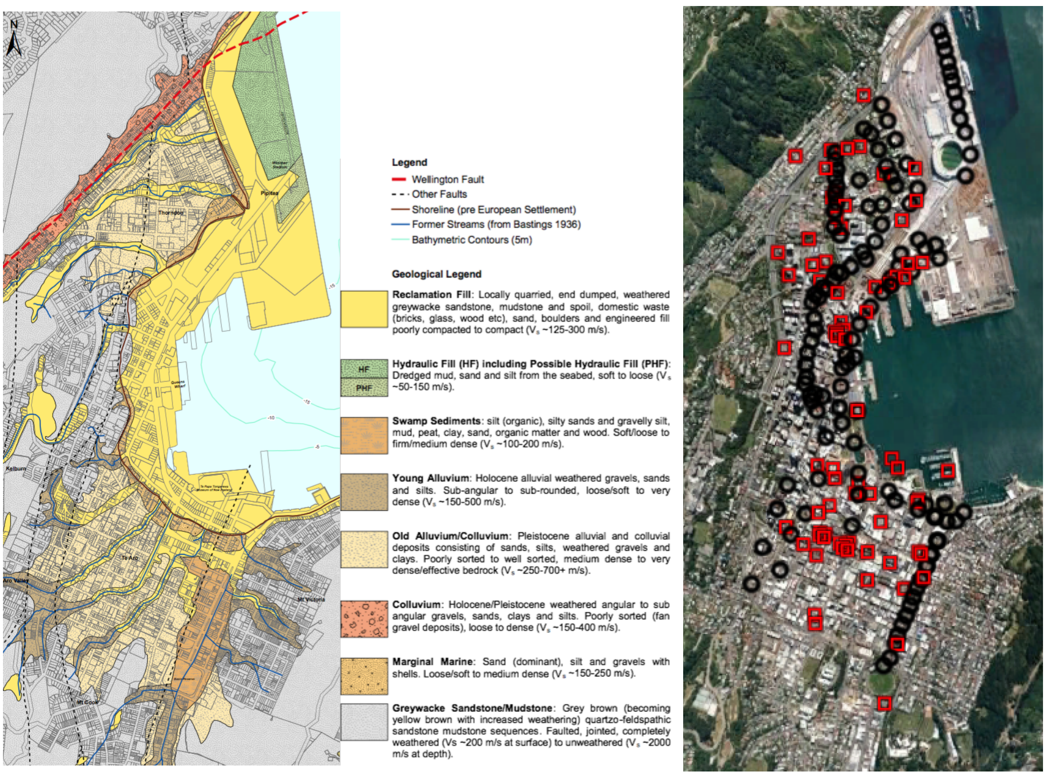
As an example of the ground motions recorded in the region, Figure 4 illustrates the acceleration time series recorded at a typical rock (POTS) and soil (TEPS) station. The ground motions at both stations are dominated by two wave packets, inferred as a result of rupture along the Jordan Thurst/Kekerengu Faults and Needles Fault, respectively [6]. The mono-chromatic nature of the shaking at the TEPS soil site is clearly evident.

Figure 5a illustrates the specific locations of nine GeoNet strong



(a) *(b)*

Figure 2: ***Spatial distribution of (a)*** $SA(T = 0.3s)$***; and (b)*** $SA(T = 1.5s)$ ***larger-component amplitudes normalised by the ultimate limit state (500 year return period) amplitudes from NZS1170.5. The outline of each circle is colour-coded by Site Class according to Kaiser et al. [16] as follows: white =B; light blue = C; dark blue = D; black = E.***



(a) *(b)*

Figure 3: (a) Semmens et al. [18] surface geology model of the central Wellington region; and (b) site investigation information - red squares indicate pre-2011 measurements of rock depth [19], and black circles indicate ambient vibration site period measurements performed since the Kaikōura earthquake [L. Wotherspoon, pers. comm.].

motion stations in the central Wellington region relative to the predominant basin edge defined by the Wellington Fault [22], and the regions of either quarry or hydraulic reclamation as a surficial soil layer [19]. It is noted that the CPLB station is the free-field instrument from the BNZ Building array, while the remaining instruments are part of the (free-field) GeoNet strong motion network. There are several reference rock stations in the Wellington/Hutt Valley region, and the (geometric mean) response spectra at five such stations are illustrated in Figure 5b. Stations POTS and PTOS are annotated, in particular, because they are considered as reference stations in subsequent figures; however, all five stations have very similar response spectral amplitudes across the full period range depicted. Because of the relatively large source to site distance, even the rock ground motions have relatively weak high frequency ground motion amplitudes (a comparison to the 500yr return period rock site design spectra [23] is provided in Figure 5b). As a result, the ground motions were not damaging to any short period structures in the region.

As noted in Figure 5a, there is significant commercial, industrial, and social activity in reclaimed regions of central Wellington. Figure 5c illustrates the response spectra at four stations located on top of reclaimed soils overlying alluvial deposits relative to that at the POTS reference rock station. Despite the proximity of the FKPS and TEPS stations, the response spectra are quite different for vibration periods less than $T = 2.0s$. This can be explained by the notably different depths of sedimentary soils between these two sites, which are inferred to be approximately 60m at FKPS and 120m at TEPS [3, 18].

The PIPS and CPLB stations, located near the northern end of Wellington City, are seen to have substantially higher spectral amplitudes than the other two reclaimed sites for vibration periods between T=0.6-6.0s. Although direct constraints are poor, Semmens et al. [19] infer that the soil depths at the location of CPLB and PIPS are on the order of 150-250m. The combination of deep sediments, variable depths of fill, and the location immediately beside the Wellington Fault resulting in long period basin-edge waves [24], are the inferred causes of the observed long period amplification.

Figure 5d illustrates three stations (WEMS, TFSS, VUWS) in the central and northern portions of Wellington City that are located on alluvial deposits, with the rock and hydraulic fill stations of POTS and PIPS for comparative reference. It is noted that VUWS has a very thin reclamation layer, but it is not expected to impact the observed ground motions at the frequencies of interest discussed here. All three alluvial sites exhibit amplification for T <4.0s relative to the POTS reference station. At long periods ($T = 2 - 6s$) the amplitudes at the TFSS site are slightly larger than the other two alluvial sites, consistent with its (poorly constrained) greater sediment depth on the order of 100m [19], compared to depths on the order of 50m for the other two sites. At shorter periods ($T = 0.2 - 1.0s$) the VUWS site does exhibit amplitudes up to 50% larger than the other two sites.

Figure 5e illustrates the observed spectral amplitudes at several other miscellaneous stations in the Wellington suburbs, with the POTS and VUWS stations providing references for rock and alluvial soil conditions in central Wellington. WNKS station is located in Karori, an elevated basin suburb located to the west of central Wellington. This site exhibits a strong spectral peak at short periods ($T = 0.4s$) with no amplification relative to the POTS rock reference station for $T > 1.0s$. This site response is indicative of resonance of shallow sediments over stiff bedrock [3]. WEL station is located just above central Wellington on a relatively small hill near its crest, with what can be seen as consistently smaller spectral amplitudes than the VUWS alluvial soil reference, but larger than the POTS rock reference. Finally, WNAS station is located at Wellington Airport, on raised beach deposits that were lifted above sea level as a result of the 1855 Wairarapa earthquake [25]. Similar to the prior comments, this site also exhibits notably smaller amplifications than the VUWS site, indicative of records in the Thorndon Basin.

The observations noted in Figure 5, and related text are generally consistent with site characteristics assessed in Kaiser et al. [16], prior site response studies [26], and observed ground motions at these locations in the 2013 Cook Strait earthquakes [27].

Lower Hutt / Petone

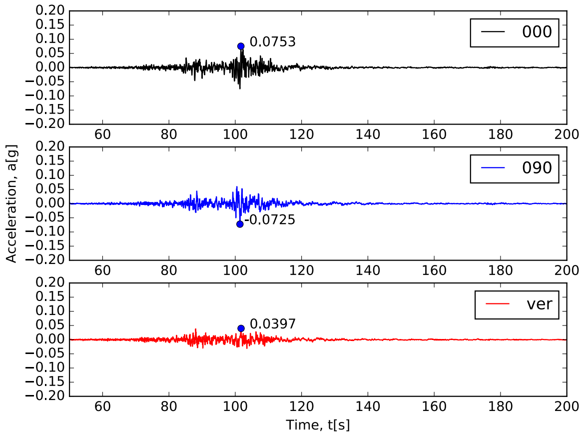
Figure 6a illustrates six strong motion stations that span the mouth of the Hutt Valley at its southern end, and provide a clear illustration of site effects in an alluvial valley that, on face value, is notably simpler than the site conditions in central Wellington. The western edge of the valley is bounded by the Wellington Fault, with sediment depths up to 300m, based on Boon et al. [17]. Progressing across to the east of the valley along the transect of stations, the basin depth gradually decreases. Figure 6b illustrates that, as seen in central Wellington, the four soil sites exhibit amplifications over the period range $T = 0.4 - 4.0s$ relative to the PTOS rock reference station. It can also be seen that over the period range $T = 1.5 - 5.0s$ there is a greater amplification for the two stations (PVCS, PGMS) located in the deeper deposits to the west than those shallower stations to the east (LHUS, LRSS). The LIRS station on the eastern boundary of the valley can be seen to exhibit mild amplification at short periods ($T = 0.2s$) from its shallow soil depth overlying rock.

SPECTRAL AMPLIFICATION COMPARED WITH CODE FACTORS

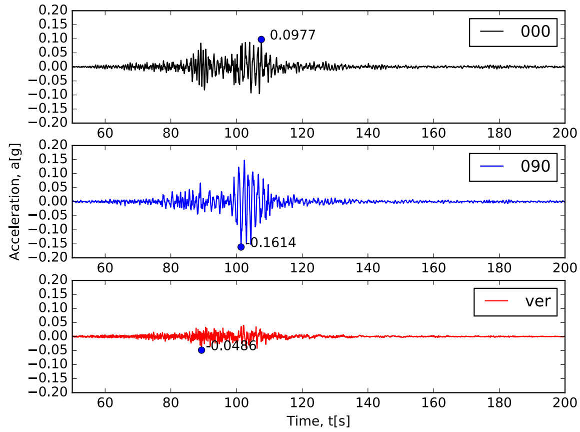
The amplitude, frequency content, and duration characteristics of earthquake-induced ground motions are a function of the earthquake source, path and site effects. Bradley et al. [6, 28] examine the consistency (or lack thereof) of the source and path effects with prediction models. Given the scope of this paper, we focus here on a comparison of the observed site amplifications as compared to those in seismic design standards - specifically NZS1170.5:2004.

Figure 7 compares the site amplification of the observed ground motions in central Wellington based on their spectral amplitude ratios with respect to the POTS reference station. For reference, the site factors prescribed by NZS1170.5 [23] are also identified. As prescribed by NZS1170.5, and shown in Figure 7, Site class C soil conditions result in a site amplification of approximately 1.25 across all vibration periods, while site classes D and E have amplifications of approximately 2 and 3.15 at long periods, which transition back to the site class C amplification for T=0.3s. It is noted that the NZS1170.5 site amplification factors are independent of any parameters other than vibration period (i.e. they are independent of ground motion intensity).

Three key observations can be made in comparing the observed spectral amplifications in Figure 7 against the code-based prescriptions. Firstly, in the vicinity of the predominant periods of the site amplification (i.e. $T \approx 1.5s$), the observed amplifications significantly exceed the code-based prescriptions. For example, sites TFSS and VUWS, which are site class D sites, have peak amplifications up to 4, as compared to the code-based maximum amplification of 2.0, whereas CPLB and PIPS amplifications are approximately 6-7 (even the site class E amplification has a maximum of 3.15). Even the WEMS site, which has an inferred site period close to the site class C/D boundary of $T = 0.6s$, has

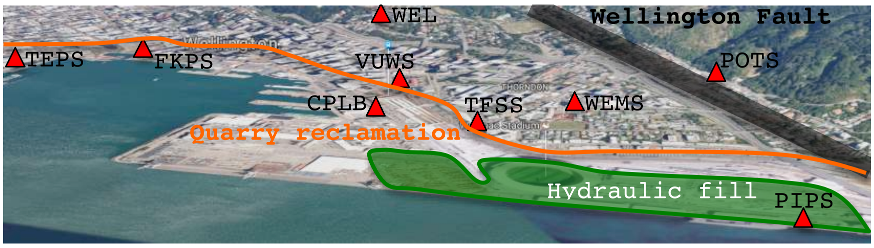


(a) Wellington Pottery Assoc., POTS (Rock)

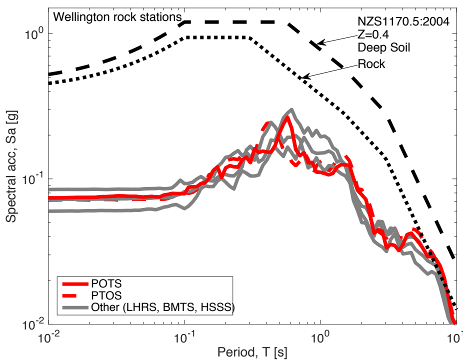


(b) Te Papa Museum, TEPS (Soil)

Figure 4: Illustrative ground motion accelerations in Wellington at POTS and TEPS stations illustrating the role of site effects relative to a reference rock station. 000, 090, and ver represent north-south, east-west and vertical components, respectively. Maximum accelerations in each component are explicitly noted. Figure modified from [6].



(a)



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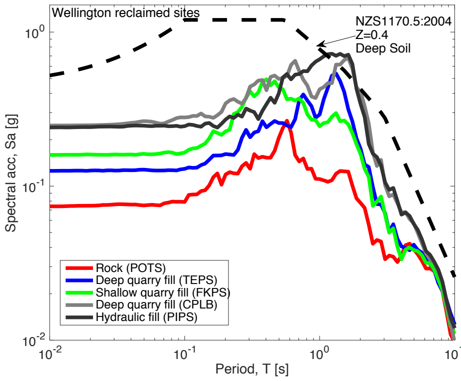

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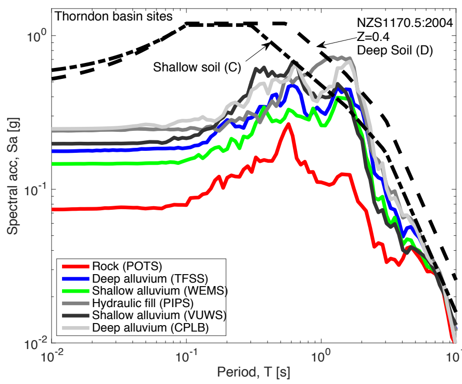
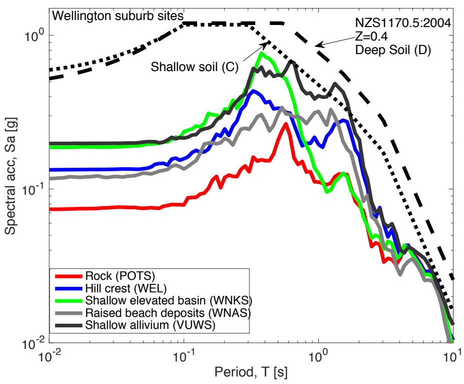
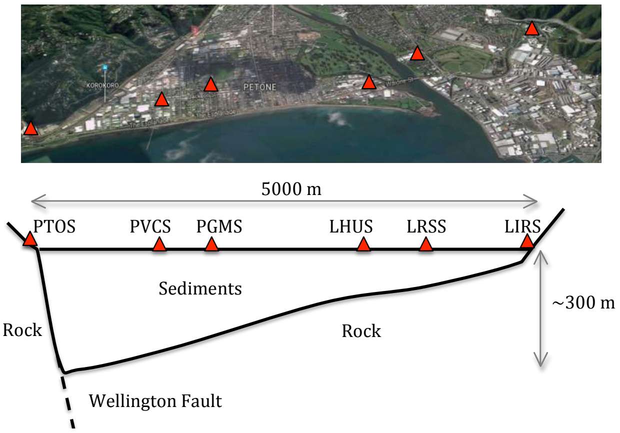


(d)

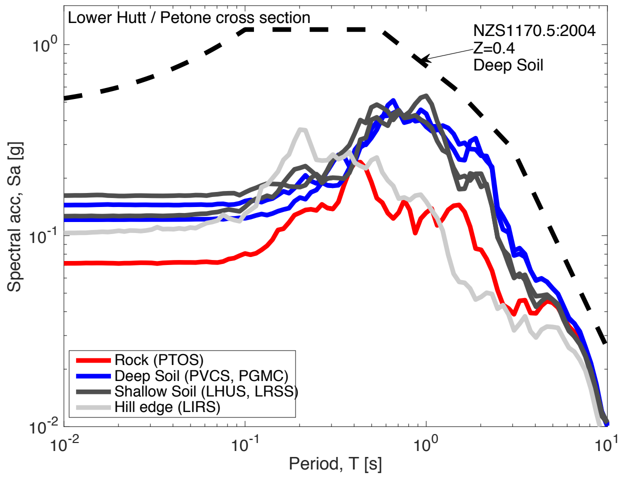


(e)

Figure 5: (a) Location of ground motion stations in central Wellington, and observed geometric mean response spectra relative to the design spectra for: (b) rock stations; (c) reclaimed sites; (d) northern central business district (CBD); and (e) suburban sites. Figure 5a notes the location of the Wellington Fault as well as areas of reclamation. Generalised near surface conditions are described in the figure legends. 'Shallow' and 'Deep' in Figure 5c indicate the total (reclamation + native) sediment depth, not simply the depth of the reclamation. Figure modified from [6].



(a) Oblique and vertical cross-section



(b) Response spectra

Figure 6: Site response effects in the Lower Hutt / Petone area: (a) Oblique view and projected vertical cross-section of the station locations at the mouth of the valley; and (b) Observed geometric mean response spectra, and NZS1170.5 site class D design spectrum for comparsion with the four soil sites. The schematic sedimentary soil depth profile based on [17]. Figure modified from [6].

spectral amplifications up to approximately 3 (compared to the site class C/D amplification of 1.25/2.0, respectively). Secondly, for long periods, $T > 4s$, the observed spectral amplifications are approximately 1.0 because this is well beyond the natural vibration periods of the sites (in contrast to the assumption of constant amplification at long periods in the code-based prescriptions). Thirdly, the short period ($T < 0.3s$) spectral amplifications significantly exceed the code-based amplification of approximately 1.25, which is largely independent of site-class. This third point is of less significance than the former two given the small short period acceleration amplitudes in Wellington from this event (because of the large source-to-site distance), and hence the lack of nonlinear site response leading to reductions in these short period amplifications.

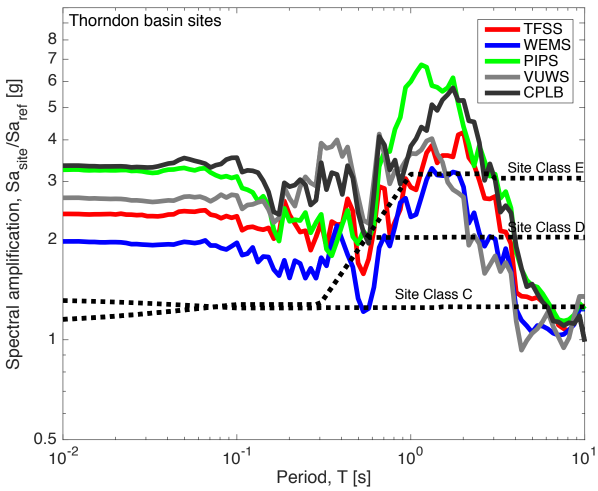


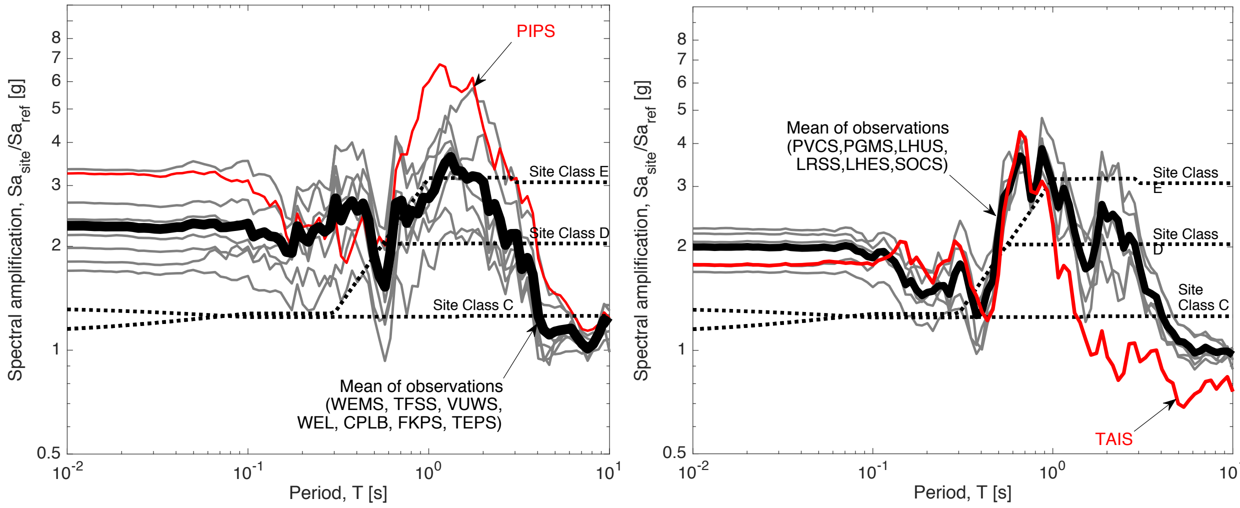
Figure 7: Spectral amplifications of five soil sites in the Thorndon basin with respect to the POTS rock station, and compared to the NZS1170.5 site factors.

From the above discussion it can be seen that, for the full period range, the code-based spectral amplification factors provide a poor comparison with those observed for the Kaikōura earthquake. In order to indicate that these observations are not specific to the Thorndon basin sites shown in Figure 7, Figure 8a illustrates all eight soil stations in central Wellington (i.e. the additional WEMS, FKPS, and TEPS stations), while Figure 8b illustrates seven soil stations in Lower Hutt (with reference to the rock record at PTOS station at Petone overbridge). While the spectral amplifications do vary moderately between the sites considered, there is a clear trend of larger spectral amplifications in the period range T=0.6-2.5s in Wellington. Because of the significant difference in site conditions at the PIPS station [19] (very deep soils on the order of 200-300m, including hydraulic fill) it is separately annotated.

While stations in the Lower Hutt basin also exhibit the same overall features in terms of spectral amplifications, there are some distinct differences from those in Wellington. Namely, the spectral amplification peak occurs at a shorter period of T=0.6-0.8s, and there is a second spectral amplification peak at approximately T=2s. Bradley et al. [6] discusses how the spectral peak at approximately T=2s in several observations in the Petone area of Lower Hutt can be tied to the fundamental period of the nearly 300m-deep sediments at the mouth of the Lower Hutt valley, while the spectral peak at T=0.6-0.8s can be related to the 30-40m thick surficial Holocene alluvial deposits (of shear wave velocities on the order of 200m/s) [17, 21]

Despite the general features seen in Figure 8, it is also important to emphasise that the actual amplitudes of the spectral amplifications do vary between some sites. For example, all of the strong motion records shown in Figure 8b come from sites in Lower Hutt which are located in the alluvial basin and designated site class D [3]. However, the spectral amplifications for T=2s vary significantly (from approximately 1.5-3.5), with the largest values occurring at sites in Petone (where the basin is deepest) and the lowest values occurring higher up the valley (where the basin is shallower). A polarising example is the TAIS (Taita School) station, which is located near the head of the Lower Hutt valley, still on site class D site conditions, but clearly exhibits no appreciable spectral amplification for $T > 1.5s$ as a result of having shallower sediment depths than the other sites.

This large variation in site response for sites which all have the same site classification, illustrates the large variation in seismic demands that would be imposed on structures built on these sites based on the same loading conditions. This suggests the need for improved formulations in design prescriptions given that such variations can be logically explained based on known geological



(a) Central Wellington

(b) Lower Hutt

Figure 8: Spectral amplifications of soil stations in: (a) Wellington with reference to the POTS rock station; and (b) Lower Hutt with reference to the PTOS rock station. PIPS and TAIS stations are specifically identified for reasons noted in the text. The mean of the remaining six stations is also shown.

and geotechnical conditions.

One final point worthy of note with respect to the observed site responses summarised in Figure 8 is the recent inclusion in NZS1170.5 [23] of a continuous transition between site classes C and D based on site period, T_1, varying in the range of T=0.6-1.5s [29]. In the form of the spectral amplification depicted in Figure 8, this revision amounts to increasing the maximum spectral amplifications from a value of 1.25 for T_1=0.6s, up to 2.0 for T_1=1.5s. However, the spectral amplification for periods longer than T=1s is still a constant value (i.e. a horizontal line in the figure). The sites in Lower Hutt shown in Figure 8b all have somewhat similar near surface conditions and vary principally in the depth of sediments that influences T_1. As a result, the observed ground motions across these seven sites exhibit a large variation in amplification at their fundamental site periods, T_1, but these amplifications are narrowband in nature (i.e. over a narrow range of vibration period, T). Even in cases of relatively shallower soil (such as TAIS), large spectral amplifications still occur close to the site period (i.e. $T_1 \approx$0.6s for TAIS; [16]), and generally significantly exceed the code-based site class C and D amplification factors.

The generalised code-based spectral amplifications inevitably result from the grouping, and subsequent averaging, of a large number of different soil deposits, each with their own narrowband amplifications over different vibration period ranges. Such amplification and its predominant period is also a function of the severity of the underlying rock ground motion intensity, which the code-based factors do not explicitly consider. However, because each piece of infrastructure resides at a single location, then the site-specific response effects will be broadly similar at a given location for future earthquakes, and hence this leads to a large variation in the demands that will be imposed on structures which have nominally the same design loading.

Using the example in Lower Hutt as indicative of site response in general, it can be emphasised that amplification occurs at the natural vibration modes of the soil deposit, with amplitudes that depend on the significance of impedance contrasts and potential nonlinear deformation [26]. The large differences between the observed and code-based site amplification factors points to the need for revision to such prescriptions, which has also been identified in a NZ government investigation [10].

SIGNIFICANT DURATION OF OBSERVED STRONG MOTIONS

In addition to amplitude, strong motion duration affects the number of repeated inelastic displacement cycles that infrastructure is subjected to, and thus the potential for the accumulation of damage. Because of their large rupture duration, large magnitude earthquakes produce long duration strong motion records. The vulnerabilities of engineered structures subject to long duration ground motion is well recognised, both from basic principles and inferences from earthquake reconnaissance observations, and also more recently from advanced numerical analyses [30–32]. However, strong motions from very large ($M_w > 7.5$) magnitude earthquakes have not previously impacted the predominant archetypes that comprise the present NZ commercial building stock.

There are various metrics that can be used to describe strong motion duration [33]. The most common is the Significant Duration, which defines the time interval over which a certain proportion of the total Arias Intensity (AI; the integral of the squared acceleration) accumulates. Significant Duration has the benefit of being largely independent of the ground motion amplitude itself, and thus provides a measure that is approximately independent of spectral acceleration amplitude.

Here the 5-95% definition of Significant Duration, D_{s595}, is adopted, which is the time interval over which 5% and 95% of AI accumulates. Figure 9a illustrates the East-West (090) component of the TFSS ground motion, the accumulation of AI, and the resulting Significant Duration of approximately D_{s595}=28 seconds.

Figure 9b illustrates the strong motion durations from the strong motion stations in central Wellington. The observed strong motions vary between approximately D_{s595}=25-30 seconds across the eight stations, and show little dependence on the nature of the site conditions.

Also shown in Figure 9b is the median and standard deviation range of D_{s595} predicted for a M_w7.8 event with a source-to-site-distance of R_{rup}=60km (the distance from the northern extent of the Needles fault rupture to central Wellington) and generic soil conditions represented by V_{s30}=250m/s (note that the prediction is weakly dependent on R_{rup} and V_{s30} within reasonable ranges).

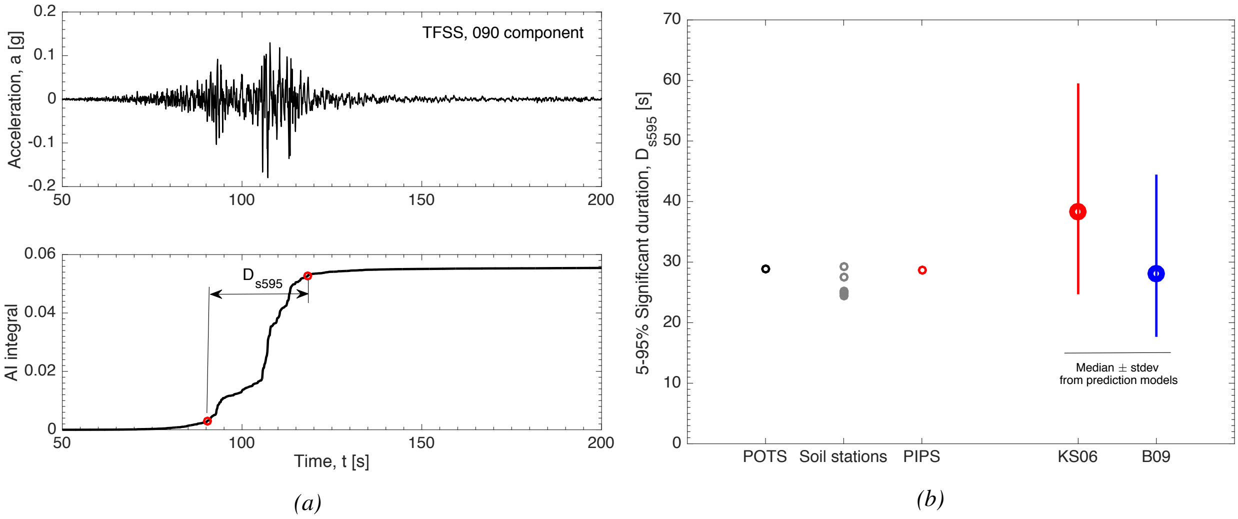


Figure 9: (a) Example acceleration time series and temporal accumulation of Arias Intensity indicative of strong motion 5-95% significant duration, D_{s595}; and (b) Comparison of 5-95% significant durations at nine central Wellington stations (POTS rock reference, six generic soil stations, and PIPS) in comparison to the median ± stdev. prediction from the empirical models of Kempton and Stewart (KS06) and Bommer et al. (B09).

Predictions using the empirical ground motion models of Kempton and Stewart [34] (KS06) and Bommer et al. [35] (B09) are both shown. Figure 9b illustrates that the observed ground motions have D_{s595} values which are similar to the median of the B09 model and are below the median of the KS06 model (although within the standard deviation range). The occurrence of significant durations below the average prediction is consistent with the broadly uni-lateral rupture of the causative faults in a general northerly direction toward Wellington [3], and thus the higher than predicted long period ground motions [36].

It is worth putting the significant durations of strong motions (D_{s595}=25-30s) in Wellington from this event in the context of the $D_{s595} \approx 10s$ and $25s$ for ground motions in central Christchurch during the 22 February 2011 M_w6.2 Christchurch and 4 September 2010 M_w7.1 Darfield earthquakes, respectively [36, 37]. That is, they are similar to those observed in central Christchurch during the 2010 Darfield earthquake (and hence why they are lower than average compared with empirical models, given that a M_w7.8 event represents an approximately 11-fold increase in the seismic moment relative to a M_w7.1 event). The predicted median significant durations of ground motions in central Wellington for a characteristic M_w7.6 Wellington fault earthquake are on the order of 10 seconds lower than those predicted for the Kaikōura earthquake [34, 35]. Finally, larger magnitude earthquakes that pose a hazard to Wellington (and other NZ regions) from the Hikurangi subduction zone could be expected to produce strong motion significant durations ranging up to those from the 2011 M_w9 Tohoku, Japan earthquake of D_{s595}=100-150s in Tokyo [37].

INFERENCES OF BASIN-REVERBERATION AND BASIN-EDGE-GENERATED SURFACE WAVES

Figure 10 illustrates the response spectra of the sites located in central Wellington segregated by their location in either the Thorndon or Te Aro basins with reference to the POTS rock station. As discussed in the previous sections, it can be seen that appreciable site amplifications occur at the seven soil sites in the horizontal directions. What Figure 10 illustrates in addition to the previous discussions is the consistently larger amplifications for the 000 (north-south) component in the Thorndon basin relative to the Te Aro basin, and also the higher vertical ground motions.

The vertical ground motion amplitudes illustrated in Figure 10c are particularly noteworthy. This is because all Wellington sites can be considered to be subject to the same underlying ground motion as a result of source and path effects (i.e. the sites are all located within 2km of each other, and over 60km from the northernmost of the causative fault ruptures). For soil deposits with shallow water tables (as is the case in all of these sites), the P-wave velocity variation within the soil profile is very mild, which would result in little site amplification for vertical P-wave propagation. This is the case for the two sites in the Te Aro basin (FKPS and TEPS), for example.

In contrast, all sites in the Thorndon basin exhibit appreciable vertical site response amplifications, particularly for periods in the range of $T = 1.5s$. The logical explanation for this observation is basin-edge-generated Rayleigh waves (which have a component of motion in the vertical direction) which occur as a result of the fault-bounded nature of the basin from the Wellington fault, or the more gradual thickening of the basin in the orthogonal, north-east, direction (Love waves are also generated, although not with the same amplitude, and don't have a vertical component, making them harder to distinguish in horizontal motion from direct S-waves).

Significant basin-edge-generated waves have been clearly documented in past earthquakes, for example, in the 1995 Kobe earthquake [24], and in Santa Monica from the 1994 Northridge earthquake [38], and previously examined from small amplitude ground motions in the Lower Hutt basin [39]. Wellington Fault rupture simulations [40] also infer significant 3D basin effects. The particular situation in Wellington is very similar to Santa Monica in that the causative faults were distant from the location of interest. As documented via observations and 2D analyses, Graves et al. [38] illustrate that basin-edge waves are most significant in the vertical direction and horizontal direction tangential to the basin edge. Kawase et al. [24] discuss the fact that because the diffracted waves are quickly converted to Rayleigh waves, which are dispersive, then the horizontal distance from the basin edge at which constructive interference of the edge and direct waves occurs is frequency dependent, with distances being greater for lower frequencies. Numerical analyses with more accurate geotechnical and geophysical representations of the near-surface soil and rock materials are needed to better understand the complex geometry of the geological setting in Wellington

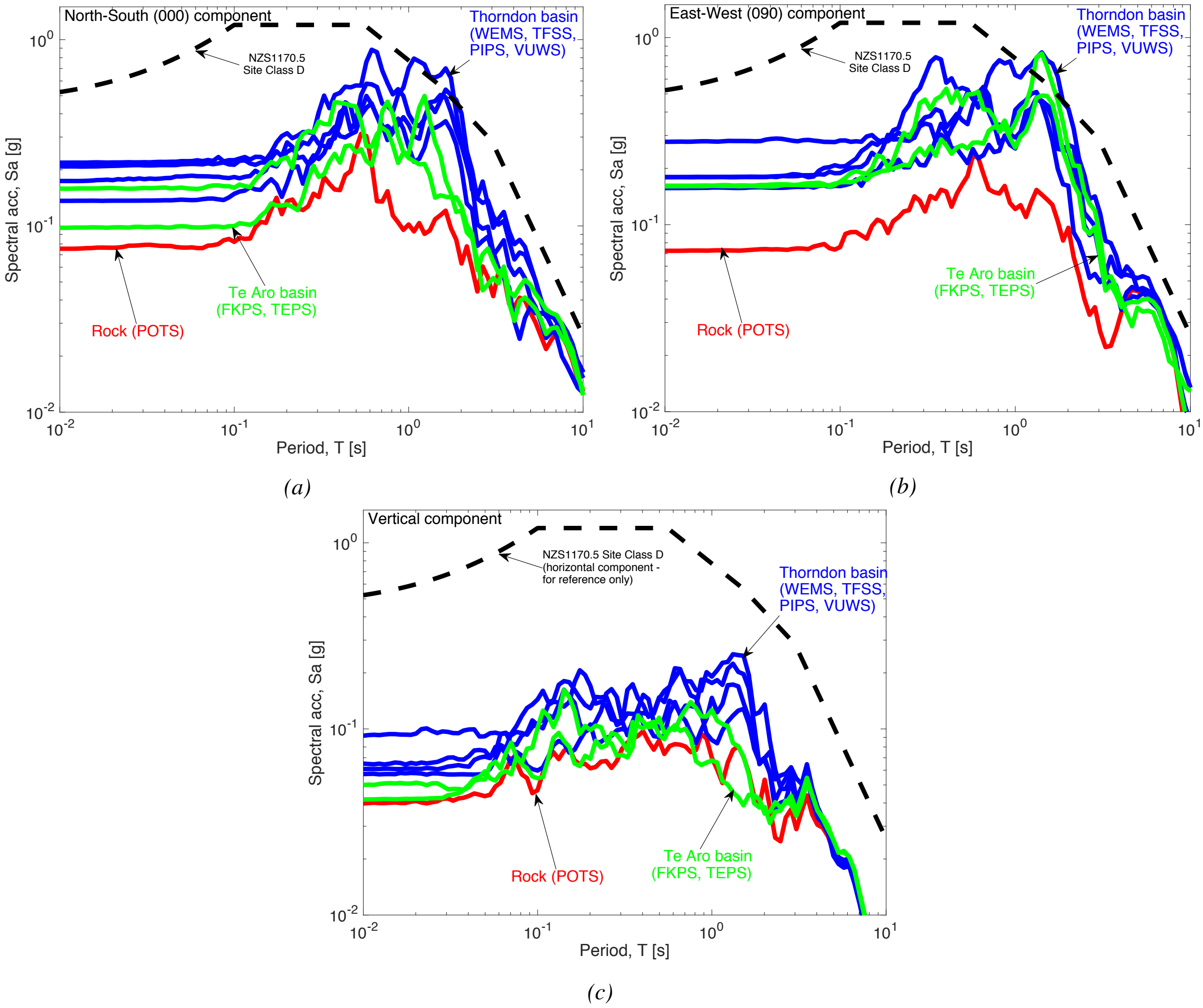


Figure 10: Comparison of response spectra in three orthogonal components: (a) North-south (000); (b) East-west (090); and (c) vertical segregated by basin location or rock.

and quantify its implications for future events. Because such basin-edge effects are geometrical- and impedance-driven, they can be expected for all events in the future, although the specific character of such effects will be influenced by specifics of the earthquake source and back-azimuth.

Drawing detailed inference on basin-edge-wave effects in the Thorndon basin is complicated by the lack of sub-surface knowledge of the basin itself. That is, while the geometry of the Wellington Fault is relatively well understood (i.e. striking at approximately 45 degrees and nearly vertical dipping), the relevance of the secondary fault structures [22] on horizontal velocity variations are not well understood, and additional knowledge of geotechnical and geophysical properties of the soil and rock units are needed to accurately characterise these effects.

COMPARISON WITH GROUND MOTION AMPLITUDES IN THE 2013 COOK STRAIT EARTHQUAKES

The Wellington region was also recently subjected to moderate intensity ground motions during the M_w6.6 2013 Seddon and Lake Grassmere earthquakes [27] (the former also being referred to as the Cook Strait earthquake). Figure 11a provides a comparison between the response spectra observed at POTS and TEPS (representative of rock and soil stations, respectively) during the 2016 Kaikōura and 2013 Seddon earthquakes. It can be seen that at short vibration periods ($T < 0.6s$) the observed ground motion amplitudes for the two different events are very similar. However, the spectral amplitudes reduce significantly at longer periods for both rock and soil sites in the Seddon earthquake in comparison to Kaikōura - specifically, at a vibration period of $T = 1.5s$ the difference is approximately a factor of two. This longer period spectral amplitude difference is the result of the larger magnitude of earthquake rupture, and consequently longer duration ground motions (for reference, the 5-95% Significant Duration of the two depicted 2013 Seddon ground motions is $D_{s595} = 10 - 11s$). These differences therefore explain the larger structural and non-structural damage observed in the 2016 Kaikōura event to multi-storey structures.

Figure 11b illustrates the site amplification at TEPS, based on the spectral ratio with the reference POTS station, in both events in comparison with the NZS1170.5 site factors. It can be seen that the site amplification at TEPS is similar in both events with a peak at T =1-1.5s, a reduction at long periods, and a short period amplification of just below 2. The differences in site amplification between the two events provide some reflection of the influence of source and path effects on site response based on response spectral ratios, but these differences can be seen to be small relative to the difference in the site factor for this site class D site. While different earthquake ruptures may induce different site effects as a result of the extent of nonlinear site response (among other factors), Figure 11b provides further motivation for research toward revising these site amplification factors.

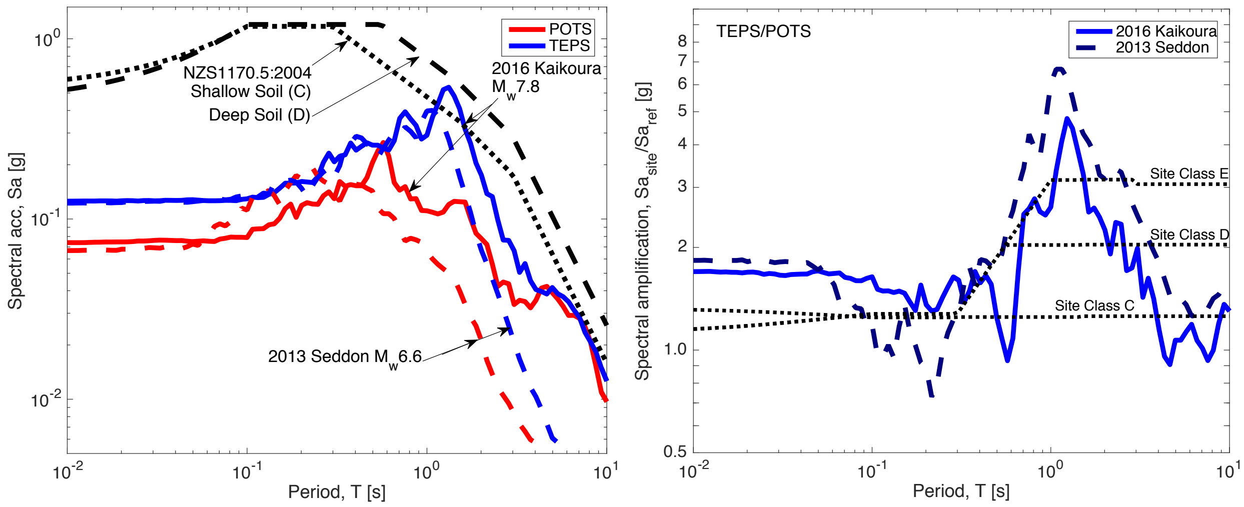


Figure 11: Comparison of ground motion observations in Wellington on soil (TEPS) and rock (POTS) stations during the 2016 Kaikōura and 2013 Seddon earthquakes: (a) (pseudo) spectral accelerations for geometric mean horizontal (solid) and vertical (dashed) components; and (b) spectral amplification of TEPS with reference to POTS relative to code-based amplification factors.

DISCUSSION AND CONCLUSIONS

This paper examined several salient aspects of the observed ground motions in the Wellington region from the 14 November 2016 M_w7.8 Kaikōura earthquake. Ground motions in the region were of moderate amplitude at short periods, but with amplitudes that approached, and in some locations exceeded, 500 year return period design levels at longer periods (principally $T = 1-3s$). Examination of the observations highlighted the role of near-surface site response and sedimentary basin effects in the spatial distribution of ground motion intensity and frequency content. Normalisation of the response spectra at soil sites by those at reference rock sites illustrated spectral amplifications which are narrowband in nature, and exceed (in some instances significantly) those prescribed by the seismic design standard, NZS1170.5:2004. Comparison with the observed ground motions in the 2013 Seddon earthquakes also demonstrated that such site amplifications are repeatable for different earthquakes that produce similar levels of underlying rock ground motion intensity.

The ground motion $5-95\%$ Significant Durations were in the range of $D_{s595} = 25-30s$, consistent with those predicted from empirical models. Such durations were similar to those affecting buildings in central Christchurch during the 2010 Darfield earthquake, and notably shorter than those expected for major subduction zone earthquakes that could affect the region.

The spatial variation and predominant frequencies of the observed ground motions can be broadly explained by the existing understanding of the sedimentary basin and near-surface site conditions in the Wellington region. However, the 3D geological and geotechnical properties in the region are evidently complex and further research is needed to characterise these materials and understand their likely response under other earthquake scenarios that will affect the region. These conclusions are supported by Recommendation 4 of the NZ government investigation into seismic response of the Statistics House building during this earthquake [10].

The consideration of site response effects in a prescriptive manner for code-based applications remains a challenge for the numerous national and international seismic design codes that exist. The clear illustration in this paper of the current unconservative nature of these amplification factors for some sites and vibration period ranges illustrates the need for an improved collection of geotechnical data to characterise sites; the development of numerical models to quantify site amplification; and the development of more realistic alternatives. A clearer pathway is also needed to enable practitioners to undertake site response analyses in leiu of code-based amplification (such guidance is currently absent in NZS1170.5), and the conservatism of simplified procedures should be more clearly conveyed in order to provide appropriate motivation for the potential use of site response analyses.

ACKNOWLEDGEMENTS

The strong motion data utilised in this paper is from GeoNet (URL: www.geonet.org.nz), which is supported by the NZ Earthquake Commission (EQC), GNS Science, and Land Information NZ (LINZ). This research is has been partial supported by QuakeCoRE: The NZ Centre for Earthquake Resilience, the Royal Society of NZ Rutherford Discovery Fellowship scheme, and GNS core funding. This is QuakeCoRE publication number 0146.

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