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Waves, layers, microtremors, earthquakes - lessons from four soft sites

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ABSTRACT: Soil-to-rock spectral ratios for earthquake motions and horizontal-to-vertical spectral ratios for microtremors ("Nakamura ratios"), are compared for four sites which are all composed of thick soft alluvium. The range of amplifications within the class "soft site" is large. The differences in amplification can sometimes be identified by studying horizontal-to-vertical spectral ratios for microtremors.

1 INTRODUCTION

The current New Zealand loadings code (NZS4203) recognises three types of site category; rock (a), intermediate (b), and flexible or deep soil (c). The divisions between these three categories are explicitly governed by the site natural period, with low amplitude natural periods of under 0.25 seconds defining category (a), low amplitude natural periods of over 0.6 seconds defining category (c), and the remainder being category (b). However it is clear (Bard & Chávez-García 1993, Chávez-García & Bard 1994) that factors other than natural period are important in determining the damage sustained by structures built on any particular site. It has been shown (Chávez-García & Bard 1994) that deeper layers can cause the predicted motion at the ground surface to be in error by a factor of three, that lateral inhomogeneities can cause destructive interference of waves, and that unexplained long duration waves can play an important role.

The question therefore naturally arises as to whether variations in the possible responses of class c sites may not be more important than variations between class b sites and class c sites. This could in principle be investigated by numerical modelling, but although modelling techniques have advanced greatly in recent years (Olsen 2000, Satoh *et al.* 2001) computational costs are still high, and investigating a comprehensive range of sites, all classified as NZS4203 class c, would be a daunting prospect. It should also be recognised that the input wavefields assumed in modelling may not necessarily reflect the conditions of an actual large earthquake.

However, in recent years a number of basin sites in New Zealand, and one in Mexico, have been thoroughly instrumented with seismographs, and investigated in detail using geophysical and geotechnical techniques. This offers an empirical means of exploring their different responses. Three of the four basin sites would definitely be classified as "c", while the fourth is marginal in that the thickest part has over 20m of soft soil, but in other parts there is less than 20m of soft soil. The sites are Alfredton (Haines *et al.* 1994), Parkway (Beetham 1999, Chávez-García *et al.* 1999), Wainuiomata (Begg *et al.*1993, Stephenson *et al.* 2002) and Texcoco (Chávez-García *et al.* 1993, Rodríguez Zúñiga *et al.* 1997). The factor common to all four basins is a layer of soft soil over 20m thick, having shear

Paper Number 65

wave velocities of the order of 100m/s at the surface. Alfredton, Parkway and Wainuiomata are relatively compact basins, only a few hundred metres wide, while Texcoco is at the eastern edge of old lake deposits which extend 20km from their western boundary near the centre of Mexico City.

All four basins have had microtremor recordings made, and analysed by Nakamura's method (Nakamura 1989). The three New Zealand sites have been intensively instrumented with seismograph arrays, and have had their geotechnical properties evaluated by means of geophysical and geotechnical methods, while the Texcoco site has limited strong-motion instrumentation and an as yet incomplete programme of site investigation. Texcoco is however included in this summary because of its tendency to prolong the duration of incident shaking, a property considered (Beck & Hall 1986) to be central to repeated observations of accentuated damage to structures built on the lake sediments of the Valley of Mexico. The three New Zealand seismograph arrays incorporated a selection of stations on the rock surrounding each basin, while the Texcoco array relies on fewer, more distant rock sites.

2 DATA ANALYSIS

For three of the four basins we have chosen to evaluate mean soil-to-rock horizontal spectral ratios over a range of earthquakes as an index of amplification. For the fourth (Texcoco), where there is limited strong motion data, we use only two earthquakes; the short history of this installation has allowed few records with reasonable acceleration amplitudes. The spectral ratios are converted to ratios of energy between rock and soil, so that the amplification effects of the various basins can be compared. Finally, the long periods of ambient vibration which were also recorded at all four sites have been converted to quasi-spectral ratios (Nakamura 1989) so that these ratios can be evaluated as predictors of increased amplification.

2.1 Alfredton

The Alfredton basin site is about 400m in diameter, with its upstream end gradually decreasing in depth. The key geophysical features are an infill material which has a shear wave velocity increasing from 80m/s at the surface to 300m/s at 20m depth, and a surrounding material with a shear wave velocity of 500-900m/s. Under these circumstances little energy is expected to be trapped in the soft layer, and indeed SCPT testing (Stephenson 1996) did not show any shear waves reflected back to the surface. Analysis of seismograms recorded on the soft infill material showed no preferred whole-basin frequencies. Some analysis of the seismograms obtained by the array has been carried out (Haines *et al*.1994, Haines & Yu 1997).

The soil/rock and horizontal/vertical spectral ratios for the basin are shown in figures 1 and 2. We note that the two curves are similar in shape and height.

2.2 Parkway

Parkway basin is also about 400m in diameter, but a representative shear wave velocity profile (Stephenson & Barker 2000) has 2m of 85m/s, overlying 9m of 150m/s, overlying 14m of 345m/s, overlying 6m of 133m/s, overlying stiff gravels. The SCPT traces show a small amount of energy reflected from depths of the order of 30m, and corresponding whole-basin frequencies of 1.7Hz have been identified (Stephenson 2000). We draw attention to the flexible layer extending from 25m depth to 31m depth, because it may have an important function in controlling basin response.

The soil/rock and horizontal/vertical spectral ratios are shown in figures 3 and 4. Note that the vertical scale has been changed by a factor of two from the Alfredton figures. It is evident that Parkway basin amplifies motion more than Alfredton basin. We note that although the two curves are roughly similar in shape and height, they differ in detail. The Nakamura ratio curve does not possess the double peak feature of the soil/rock ratio curve.

2.3 Wainuiomata

The Wainuiomata basin is some 2km in length and 800m wide and is filled with lacustrine sediments

(Begg *et al.*1993). Early measurements of shear wave velocity (Stephenson & Barker 1992) revealed a 22m thick layer of 90m/s material overlying 9m of 150m/s material, overlying stiff gravels. Strong reflections in this SCPT test corresponded to the 0.8Hz spectral peak commonly observed e.g. (Cousins 1995).

The soil/rock and horizontal/vertical spectral ratios are shown in figures 5 and 6. Here the vertical scale is changed by a factor of six with respect to Alfredton. Clearly Wainuiomata amplifies much more than either Alfredton or Parkway. The resonant peaks of the two curves are identical in frequency, but differ in amplitude by 50%, while the horizontal/vertical ratio curve drops to a low value at 1.96Hz in agreement with the particle orbit of a Rayleigh wave.

2.4 **Texcoco**

The Texcoco basin (Marsal & Mazari 1990, Marsal 1978, Mooser *et al.* 1986) is some 25km across, and like Wainuiomata, is an infilled lake. The infill material is extremely flexible, with a varying thickness that gives rise to natural frequencies of between 1.0Hz and 0.25Hz. (Lermo & Chávez-García 1994). The Texcoco array site (Lomnitz *et al.* 1999), is situated on undeveloped land to the northeast of Mexico City's airport. It was chosen in preference to other Valley of Mexico sites because it incorporates instrument spacings of 400m, 35m and 4.5m and has a vertical array of accelerometers at 2m, 10m, 20m, 30m and 40m depth. Such a configuration allows the ground motion to be measured with unprecedented detail. Its undeveloped location makes future field measurements simple.

The soil/rock spectral ratio is shown in figure 7. It is computed from the horizontal motion of the 1999 September 30 magnitude 7.5 earthquake located near the coast of Oaxaca, and the horizontal motion of the 1999 June 21 magnitude 6.3 earthquake located in Guerrero. The soil station was TXS1 in Texcoco and the rock station was at Estanzuela, 14km from the Texcoco array. The records from the smaller (June) event were multiplied by 12 in order for them to be comparable in amplitude with the September event, prior to separately adding the soil and rock spectra and forming a mean ratio. With only two earthquakes being used there is some potential for the mean ratio to deviate from what may be observed for many earthquakes. However, the peak spectral ratio value is in good accord with previously cited estimates (Lermo & Chávez-García 1994) for sites in the Valley of Mexico.

The horizontal/vertical spectral ratio for microtremors is shown in figure 8, appearing as a low peak at 0.31Hz. The high peak and associated trough seen in Wainuiomata data are not seen in Texcoco data, for an unknown reason, casting doubt on the unsupported use of such ratios to evaluate sites. However, the red line in figure 8, which shows the horizontal/vertical spectral ratio for ground motions measured during the 1999 June 21 earthquake, suggests that a resolution of this problem may lie in examining the differences between the waves that are associated with microtremors and the waves that are associated with earthquakes.

3 INCREASE OF SHAKING ENERGY

Because our data is in the form of soil/rock spectral ratios, we have chosen to quantify the increase in shaking by considering the area under a curve which is the ratio of soil/rock power spectra. This is very similar to the concept of Arias intensity (Arias 1970), and represents the soil/rock energy ratio. An idea of the significance of our energy ratios is gained by calculating the ratio for the site L02 in Lower Hutt, New Zealand, from measured soil/rock spectral ratios (Taber & Smith 1992). The soil/rock energy ratio is 4.86 for this site, which was assessed (Van Dissen *et al.* 1992) as having minimal amplification. The values for the four basins studied are Alfredton, 5.29; Parkway, 8.36; Wainuiomata, 22.3 and Texcoco, 21.6 . It is clear that in strong earthquake shaking Wainuiomata and Texcoco could be associated with much greater structural damage than Alfredton and Parkway, even though all four sites appear to belong to the same class. Of course this conclusion would only apply if the rural areas of Alfredton and Texcoco became developed. The crucial fact is that Alfredton differs little from L02 in its amplification, and consequently behaves much as a firm gravel site would.

4 DISCUSSION

This study has shown that there are large differences between the soil-induced amplifications of earthquake motion at four sites which, according to the provisions of NZS4203, would all be classified as class c due to their site periods. These differences could be ascribed to differences in the input rock motion, with soft rock under a soil site pre-amplifying the deep bedrock motion, resulting in a low soil/rock ratio even though the soil motion has been amplified in the course of its journey from deep bedrock. However it has been shown (Chávez-García & Bard 1994) that deeper layers can cause the predicted motion at the ground surface to be in error by a factor of three, that lateral inhomogeneities can cause destructive interference of waves, and that unexplained long duration waves can play an important role. Furthermore the rock sites relevant to Parkway and Wainuiomata have very similar shear wave velocities, suggesting that the differences in amplification have less to do with the properties of the underlying rock than they have to do with the properties of the soil layers.

In view of the period-based class divisions of NZS4203 it is tempting to think that differences in site period might account for the differences in amplification. However Texcoco and Wainuiomata have different periods but similar amplification, arguing against this idea. Perhaps differences in soil shear-wave velocity could provide an alternative cause of different amplifications, with flexible sites tending to amplify more than stiff sites. However if this were the case the amplifications at Alfredton and Parkway would not be expected to differ as much as they have been observed to do.

As the different amplifications appear to depend on the detailed properties at each site rather than on a single simple variable such as site period or shear wave velocity, the need for a simple measurement that can directly give amplification becomes evident. Although Nakamura’s method often seems promising in this respect, the Wainuiomata and Texcoco results sound a warning. Given the sharp resonant peaks obtained for soil/rock spectral ratios at Wainuiomata and Texcoco, it is surprising that the Nakamura ratio curve at Texcoco does not resemble the one at Wainuiomata. The reason for this discrepancy is unknown.

Given that the range of responses of class c sites is large, it is valid to ask whether the same applies to classes a and b. Relevant information is scant, but Taber and Smith (1992) note differences in response between weathered greywacke and unweathered greywacke. However these differences appear to be less than the difference in amplification between Alfredton and Wainuiomata. Another approach which may be applied to evaluating the range for class a is to consider variations of shear wave velocity for rock on the basis that stiffer rock will be associated with smaller input motion to the soil. According to Melhuish and Bannister (1995) the limestones of Bluff hill, Napier, New Zealand have velocities as low as 250m/s, but are classified as rock by Dowrick *et al.* (1995) using NZS4203 criteria, while basalts for example might be expected to have shear wave velocities an order greater. Hence it is a reasonable expectation that there will be considerable variation in the amplification of earthquake ground motion within class a.

5 CONCLUSIONS

- The variation in amplification within a range of “soft sites” is large.
- The variation in amplification cannot be explained by simplistic appeals to the single variables of site period or shear wave velocity.
- The variation in amplification can sometimes (but not always) be identified by studying HVSR values for microtremors.

6 ACKNOWLEGEMENTS

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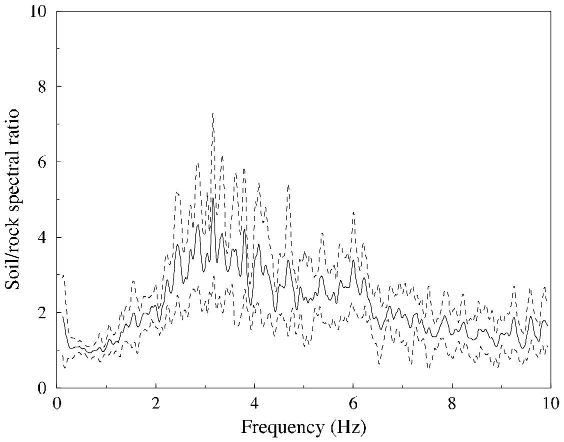

Figure 1. Soil-to-rock spectral ratio for earthquakes recorded in the middle of the Alfredton basin. The dashed lines are ± 1 standard deviation.

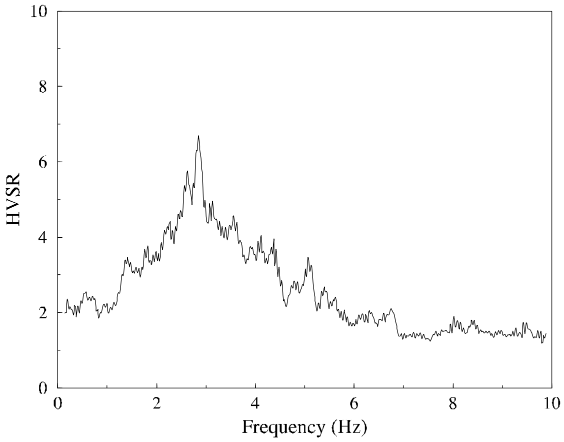

Figure 2. Horizontal-to-vertical spectral ratio for microtremors recorded in the middle of the Alfredton basin. Insufficient data was recorded to determine meaningful standard deviations.

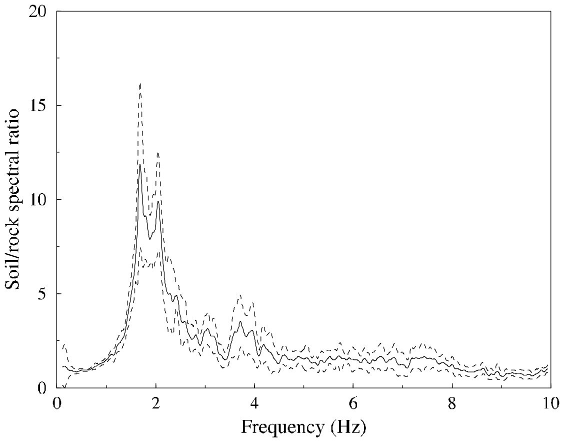

Figure 3. Soil-to-rock spectral ratio for earthquakes recorded in the middle of the Parkway basin. The dashed lines are ± 1 standard deviation.

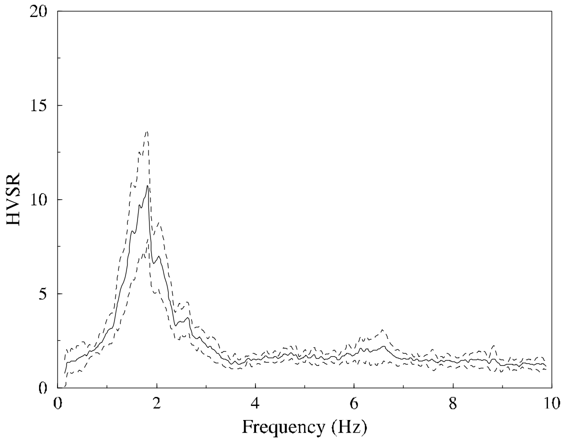

Figure 4. Horizontal-to-vertical spectral ratio for microtremors recorded in the middle of the Parkway basin. The dashed lines denote ± 1 standard deviation. The fine structure differs from that obtained for soil-to-rock spectral ratios.

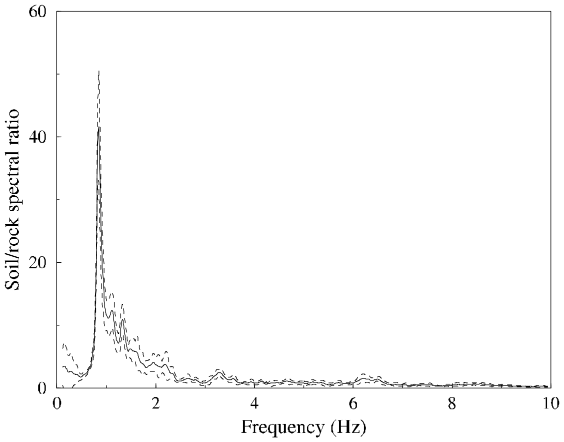

Figure 5. Soil-to-rock spectral ratio for earthquakes recorded in the middle of the Wainuiomata basin. The dashed lines are at ± 1 standard deviations from the mean. Note the scale change from the previous figures, and the high resonant peak

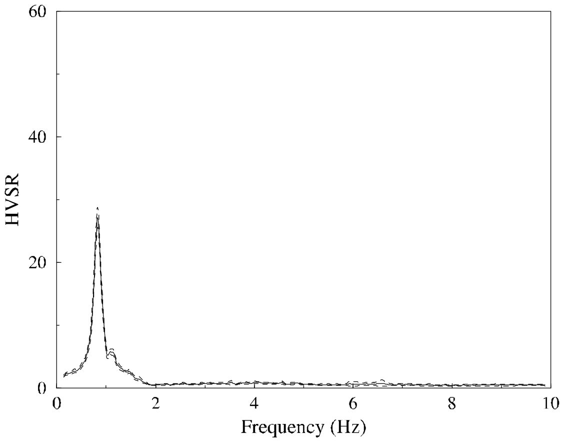

Figure 6. Horizontal-to-vertical spectral ratio for microtremors recorded in the middle of the Wainuiomata basin. The dashed lines denote ± 1 standard deviation. The resonant peak is at the same frequency as for soil-to-rock spectral ratios, but its amplitude is smaller.

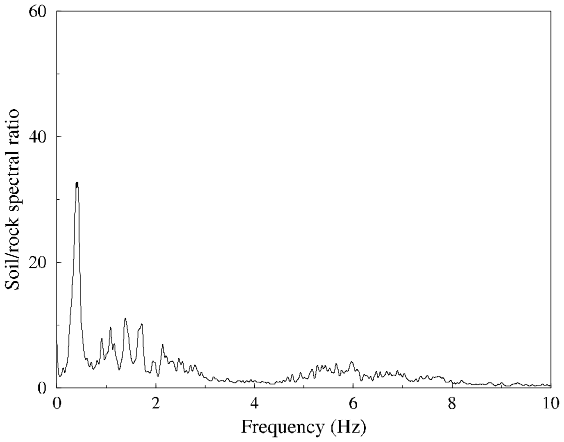

Figure 7. Soil-to-rock spectral ratio for earthquakes recorded at the Texcoco array. There was insufficient data to calculate a meaningful standard deviation. The scale is the same as for Wainuiomata

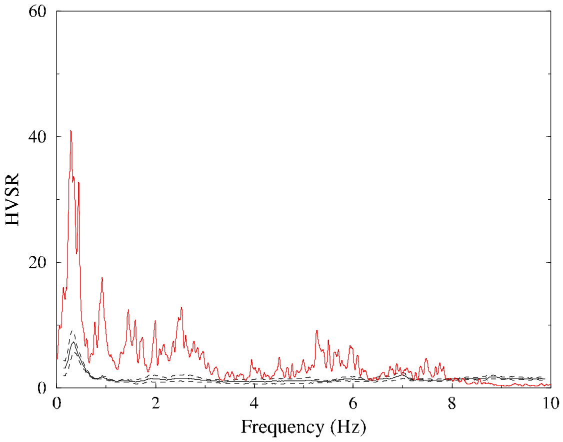

Figure 8. Horizontal-to-vertical spectral ratios for microtremors (black) and an earthquake (red) recorded at the Texcoco array. The dashed lines denote ± 1 standard deviation. The resonant peak is at the same frequency as for soil-to-rock spectral ratios, but its amplitude is smaller. HVSR for earthquake motion is a better predictor of amplification, than HVSR for microtremors