

MICROTREMOR SURVEY DESIGN OPTIMISED FOR APPLICATION TO SITE AMPLIFICATION AND RESONANCE MODELLING

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ABSTRACT

Microtremor surveys at their simplest level of measurement (single three-component geophones) provide the natural period of site resonances which may be used as a first-order tool in zonation of earthquake risk. At a second level of measurement, the use of a circular array of geophones enables calculation of the phase velocity of propagation of microtremor energy, from which estimates of the shear-velocity profile and thickness of unconsolidated sediments can be derived without recourse to invasive site testing such as drilling or cone-penetrometer measurements.

The shear-velocity profile and thickness of sediments obtained from microtremor data are suitable as direct inputs into computation of site amplification and resonances using SHAKE software. This paper shows that site-resonance data alone is insufficient for adequate calculation of site-amplification effects, but site-resonance data combined with microtremor velocity information is a potentially powerful micro-zonation methodology.

1. INTRODUCTION

The use of high-frequency background seismic noise, known as microtremors, for site resonance classification is well established; see the companion paper in this volume (Asten and Dhu, 2002) for a review of information available from single-station measurements of horizontal and vertical microtremor spectra.

Traditional micro-zonation methodology based on the Nakamura (1989) method uses the fundamental site resonance period (T_s) to characterize the potential site hazard levels. Site resonance can result in significant amplification of the structural response but it can be suppressed very effectively by damping or other energy dissipation mechanisms in the structure. For this reason, aseismic design of ductile construction in active regions does not normally include resonance considerations in their design calculations. In contrast, non-ductile or limited ductile structures typical of low and moderate seismicity regions such as Australia are particularly vulnerable to site resonance due to the poor energy absorption capacity in these structures. For such conditions, T_s seems to be particularly important since the higher the value of T_s the higher the displacement demand of structures found on the soil surface.

However, T_s on its own is not fully indicative of the extent of resonance related amplification which also depends on period shift, hysteretic damping and radiation damping at the soil-rock interface, amongst other factors. Period shift and hysteretic damping are the result of non-linear behaviour in the soil layers. The extent of such behaviour depends on soil depth and properties such as the plasticity index. The presence of a very soft soil layer could also result in anomalous response behaviour of the site. Radiation damping at the interface between two wave transmission media (ie rock and soil) depends on their wave velocity contrasts. For example, severe resonance is often resulted from waves trapped within a very soft (low shear-wave velocity) soil medium that overlies a very hard (high shear-wave velocity) bedrock medium. In contrast, resonance is muted when substantial amount of wave energy is dissipated into "soft" bedrock.

The multitude of factors influencing soil responses as outlined above suggests a major drawback in the traditional approach of using T_s as the sole parameter to define the potential site hazard. There are further obvious drawbacks where, for example, the upper soil layers are to be excavated for basement construction. Information related to soil depth, soil properties and shear wave velocity of individual soil layers and bedrock is traditionally obtained by site drilling and testing of soil samples. Whilst multiple site drilling may be justified for major construction projects, employing the same approach for micro-zonation studies (which typically cover a very large areas) would be too costly and is generally not practical.

As pointed out earlier, mapping of the T_s from single-station micro-tremor monitoring is not on its own sufficiently indicative of the soil profile and hence cannot be used as effective substitutes for conventional site drilling. The multiple-station non-invasive micro-tremor monitoring method demonstrated in this paper offers a viable solution to this problem. This new monitoring procedure produces the shear wave velocity profile and not just T_s . Such profiling can assist in identifying the entire geological formation of the site when properly integrated with existing borehole information.

This paper considers three soil sites which possess similar fundamental site period but with very different soil depths and shear wave velocities. It is first demonstrated in Section 2 that single-station measurements of the H/V ratios (based on the conventional Nakamura

approach) could not distinguish between the three sites. In contrast, the coherency measurements obtained from a circular array of six geophones as presented in Section 3 managed to identify the site shear wave velocity profile with good resolution. The engineering significance of distinguishing between the sites is demonstrated in Section 4 which compares soil response spectra associated with the individual shear wave velocity profiles.

2. NATURAL PERIOD METHODS

The seismic energy associated with microtremors propagates principally in surface-wave modes. Measurement of vertical-component seismic noise excludes Love modes and allows study of the data in terms of Rayleigh modes of propagation. Rayleigh-wave energy propagates with elliptical particle motion, where the ratio of horizontal to vertical-motion particle motion is dependent on wave period and the compressional and shear elastic parameters of the earth. At shear-wave resonance frequencies the particle-motion ellipse tend to degenerate into dominantly horizontal motion, hence the use of H/V spectral ratios is a very useful guide to the *period* of such resonances. However as demonstrated by Lachet and Bard (1994), the spectral ratio is a poor indicator of *amplification* at the resonance period, since amplification is also a function of Poisson's ratio.

Figure 1 shows the H/V spectrum from a recording over Barrier Sand at Blacksmith, south of Newcastle (NSW). The thickness of sand and weathered bedrock is a minimum of 30 m (SCPT test) and may be up to 60 m. The spectrum shows a strong maximum at period 0.85 s, with a lesser secondary peak around period 0.3 s.

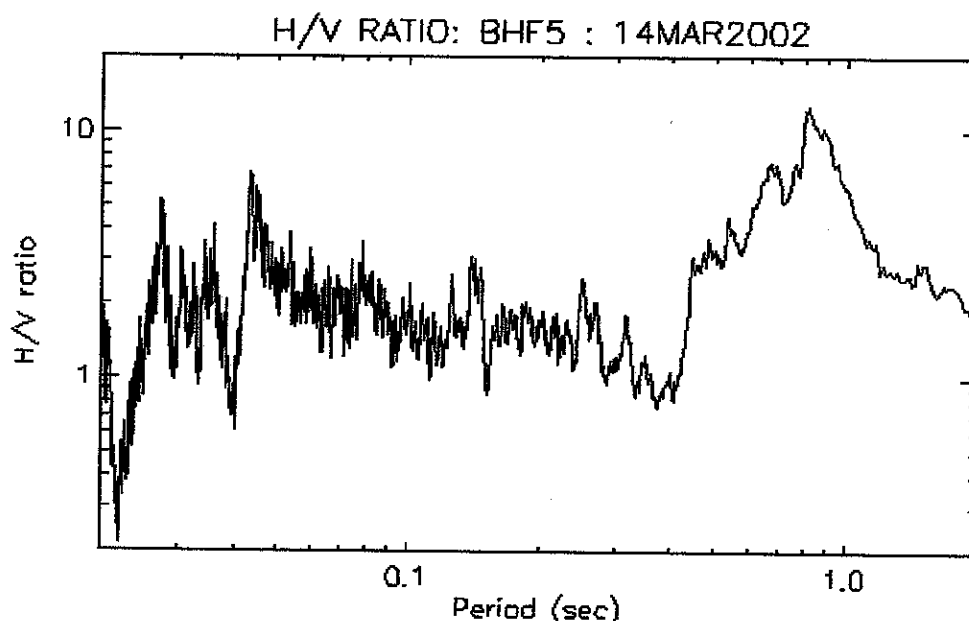


Fig.1. H/V spectrum for 100 s of microtremor data recorded at Blacksmith.

Table 1 shows a useful generic layered-earth elastic parameter model for the Blacksmith site. The model consists of two unconsolidated layers of sand overlying a sandstone rock basement (also underlain at 1000 m depth by granite). Shear velocities for the upper two layers are derived from a SCPT measurement in the locality, about 1 km to the east (Dhu et al, 2002). Table 1 also shows two additional models derived from the first by respectively halving and doubling the thickness of unconsolidated material while maintaining the (shear velocity x thickness) product constant. The three models have equivalent resonance period for the fundamental shear-wave resonance, and Figure 2 shows that the modelled H/V

particle motion ellipse for the first three Rayleigh wave modes shows maxima at similar periods (0.85 and 0.3 s), where we have modelled the wave motion using the method of Herrmann (2001). The similarity in period of the H/V maximum demonstrates that simple resonance studies cannot distinguish between these three models, and hence in the absence of independent information, the shear modulus of the site for the purpose of foundation design is similarly poorly defined.

Table 1 Soil profiles of resonance-equivalent sites

Soil layers	Model 1 (Blacksmith)		Model 2 (thick regolith)		Model 3 (thin regolith)	
	Thickness (m)	V _s (m/sec)	Thickness (m)	V _s (m/sec)	Thickness (m)	V _s (m/sec)
1 st layer	6.5	140	13	280	3.25	70
2 nd layer	45.5	250	91	500	22.25	125
bedrock	1000*	1700	1000*	1700	1000*	1700

The sandstone bedrock is underlain by granite (V_s=3490m/sec) at a depth of 1km.

The density of the soil layers and sandstone is taken as 1.78tonne/cum and 2.39tonne/cum respectively.

3. PHASE VELOCITIES FROM MICROTREMORS

Phase velocities of microtremors may be estimated using beam-forming techniques (eg Liu et al, 2000) or azimuthal averaging. We use the latter for reasons summarised in Okada (1997) and Asten (2002). Use of a circular array allows sampling of the propagating microtremors over a range of azimuthal angles. For each pair of stations the coherency may be computed by standard spectral analysis methods (eg Koopmans, 1974). The circular array thus samples coherency over a range of azimuths. The averaging of these coherencies over azimuth provides a new parameter which, provided wave energy is confined to a single scalar velocity at each frequency, can be shown (Aki, 1957; Asten, 1976, 2001; Okada, 1997 and references therein) to take the form

$$ave\ c(f) = J_0(kr) = J_0(2\pi fr/V(f)), \quad \text{----(1)}$$

where *ave c(f)* is azimuthally-averaged coherency,
f = frequency, *J*₀ is the Bessel function of zero order,
k is the scalar wavenumber, *V(f)* is the required phase velocity dispersion curve, and
r is the station separation in the circular array.

We now compare field and modelled *ave c(f)* for the sample of field data whose spectrum appears in Figure 1. A seismic array of six geophones arranged in a circle (hexagon) about a central geophone (following Asten, 2001) allows computation of *ave c(f)* for the field data, shown in Figure 3. Using the generic layered-earth model given in Table 1, we calculate the theoretical Rayleigh-wave phase-velocity vs frequency dispersion curves (not shown in this paper, but see Asten and Dhu, 2002, this volume, for examples). The theoretical velocity-frequency data is then substituted into equ(1) above (with *r*=50 m as for the field seismic array) to obtain a theoretical curve of *ave c(f)* vs frequency.

Figure 3 shows three examples of the modelled curve for *ave c(f)*, computed for each of the three regolith models shown in Table 1. It is obvious that the modelled average coherency curves for the thick-regolith and thin-regolith "resonance-equivalent models" bear no relation to averaged coherencies for the field data. Study of sensitivity of fitting of the theoretical and model curves indicates that the four parameters important to foundation design, namely thickness and shear velocity of the two unconsolidated layers, can be resolved to within about 20% by interactive visual fitting of the field data with varying

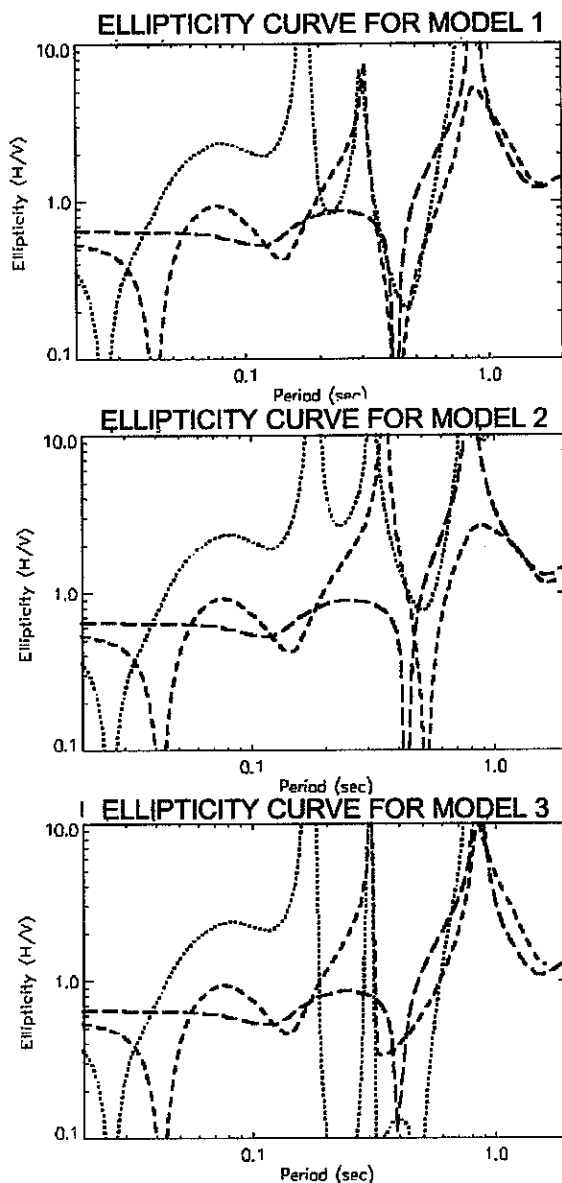


Fig.2. Computed H/V ellipticity vs period for three layered-earth models shown in Table 1. Dashes: Fundamental Rayleigh mode. Short dashes: 1st higher mode. Dots: 2nd higher mode.

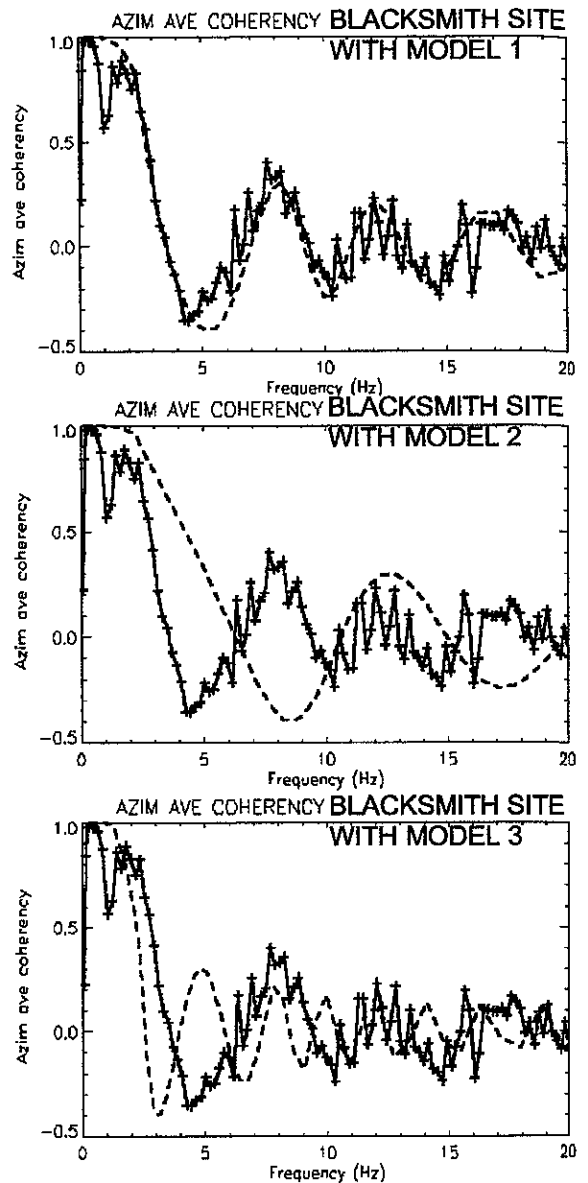


Fig.3. Fit of averaged coherency of field data (solid line) with modelled coherency (dashed line), for the three models given in Table 1.

model data. Formal inversion methods under development are expected to bring higher resolution.

4. COMPUTATION OF RESONANCES FOR THREE SITE MODELS

We now consider how the constraints on soil shear velocity, obtained from microtremor velocity measurements in the previous section, impact on resonances as calculated for building design.

One dimensional non-linear shear wave analyses (using program SHAKE) have been undertaken to determine the soil response spectra for the three "resonance-equivalent"

models for which details of the soil layers have been summarized in Table 1. The rate of modulus reduction with increasing soil strain assumed for these analyses is based on the model defined by Lam and Wilson (1999) for cohesionless soils. It is shown that the adopted rate is very consistent with the "mean" recommendations by Seed & Idriss (1970). As shown in earlier sections of this paper, all three models possess similar natural period of about 0.9 secs but very different soil profiles. Model no.1 is the original profile recorded near the Blacksmith site using SCPT measurements, whereas Model no.2 has been modified to include deep, stiff soil layers totaling 100m in thickness. In contrast, Model no.3 has a total thickness reduced to 25m, but with soils of proportionately lower shear strength. The bedrock excitation employed in the analyses possesses a PGV of 50-60 mm/sec which is generally consistent with the ground motion intensity level stipulated for Australian capital cities for the 500 year return period.

The velocity response spectra of the three soil sites are similar in shape, with the highest point of the spectrum at the resonant peaks being consistently about 4 times higher than the corresponding level in the bedrock spectrum (Figure 4a). This observed amplification is in agreement with the prediction by a simple manual method developed very recently for modelling the effects soil resonance (Lam et al, 2001). Significantly, the period at resonance is well above the notional 0.9sec and varies between 1-1.5secs depending on the soil profile. The resonance period variation results in very different peak displacement demand as shown by the corresponding displacement response spectra (Figure 4b). The significance of period shift is thus well demonstrated. The notably higher period shift in the thin-regolith model (no. 3) is considered to be the result of non-linear behaviour in the soil. Non-linearity is clearly most pronounced in the very soft shallow soil site due to the higher angle of soil shear deformation compared to a stiff deep soil site. The peak displacement demand is shown to differ by as much as 50% between the resonance-equivalent sites.

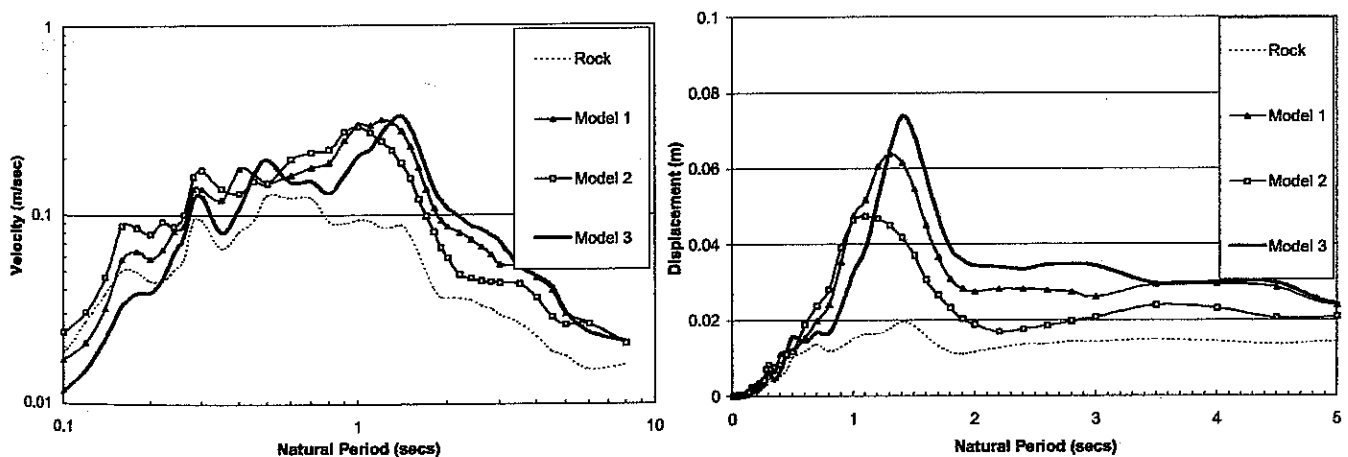


Figure 4 Velocity and Displacement Response Spectra for soil sites and bedrock

5. CONCLUSIONS

While site classification by natural period using observations of microtremors is a useful aid in assessing risk of damage from earthquakes, it is also subject to some ambiguity unless either the shear velocity or thickness of unconsolidated soil and sediments are known independently (such as with SCPT measurements). However the measurement of phase velocities of microtremors using a small circular array of seismometers, instead of a single station, provides sufficient information to determine the soil shear-velocity profile to within about 20%, thus allowing independent estimates of shear velocity, or extrapolation of existing drilling or SCPT measurements.

SHAKE modelling, using the shear-velocity profile derived from microtremor data, demonstrates that the ambiguities inherent in the use of natural-period measurements alone, may result in errors of order 50% in calculations of displacement demand. Such modelling quantifies the resonance period and site amplification which are of prime importance. It also shows the importance of non-linear behaviour of soils, which perturbs the frequency of maximum amplification to longer periods than that indicated by simple microtremor period measurements. We note that all analysis considered in this paper is restricted to layered-earth models; additional provisions may need to be incorporated in site classification studies to account for non-horizontal stratification of the soil layers, where the potential benefits justify the additional costs.

We conclude from studies thus far that microtremor velocity measurements have a significant role in improving inputs to site-amplification studies.

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