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MICROZONATION OF THE EXPECTED SEISMIC SITE EFFECTS ACROSS PORT VILA, VANUATU

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The city of Port Vila, Vanuatu, is located in one of the most active seismic regions on earth. Earthquakes are felt frequently and, due to very rapid plate convergence rates, return period of large earthquakes ($M > 6$) in the New Hebrides Benioff zone can be less than 10 years. Even though Port Vila does not lie on an identified seismic fault zone, strong motions by nearby earthquakes have to be expected due to the city's geographical location close to the plate boundary of New Hebrides convergence zone. An accurate estimation of the seismic ground motion across the city is of prime importance for urban developments and mitigation of earthquake risk. Following many examples of monitored strong earthquakes in the current century, it is evident that the local site effects may have a dominant contribution to the intensity of damage and destruction. In this study we focussed on the first stage of associating site effects and seismic hazard by preparing a microzonation map for Port Vila. The seismic microzonation of the city has been carried out to provide a detailed map of the zones that exhibit site effects in terms of resonance frequencies and approximated amplification of the ground shaking. Having in mind that these data will be used in improving building design to sustain strong ground motions, our analysis is limited to the frequency band of 1–10 Hz, corresponding to the expected resonance of different types of buildings in Port Vila. The Nakamura technique has been used to estimate site amplification effects from single station noise recordings. Interestingly, excluding one site located on an old dump zone, the amplification factors at about the 100 sites surveyed in Port Vila remain below 3 with an average well below 2 in the 1 to 10 Hz frequency band. These results suggest that there is no significant Vs velocity change in consequently layered material and that the uppermost sedimentary layers in the surveyed down town area are relatively thin. These observations are in agreement with the mapping of limestone terraces throughout Port Vila area. However, both the surface geology and results from seismic zonation indicate a thicker (up to several tens of meters) sedimentary cover around the Bauerfield airport and in the Méle terrace zone. Low resonance frequencies (around and below 1 Hz) and amplification factor of the order of 5 were observed over this large area, immediately outside Port Vila. Any building development in this area should take these results into account.

1. Introduction

The epicenters of earthquakes with moment magnitude of 5 or more for the period 1977–1997 (from the Harvard CMTS catalogue) in the Efate segment of the New Hebrides subduction zone in Vanuatu are shown in Fig. 1. Port Vila, due to its proximity to those seismic sources, is vulnerable to strong earthquakes. Diagrams of cumulative coseismic slip versus time give the NH subduction zone a maximum magnitude earthquake of 8.6. A mean return period of 480 years for this maximum magnitude has been estimated from a Gutenberg–Richter frequency magnitude relationship diagram (R. Pillet, personal communication). Along the NH island arc, the average recurrence interval for a magnitude 8 earthquake is about 10 years.

Evidently, proximity to high magnitude events is not the only controlling parameter of the earthquake damage. Major variations in the damage rate observed during strong earthquake at adjacent locations with different geology and

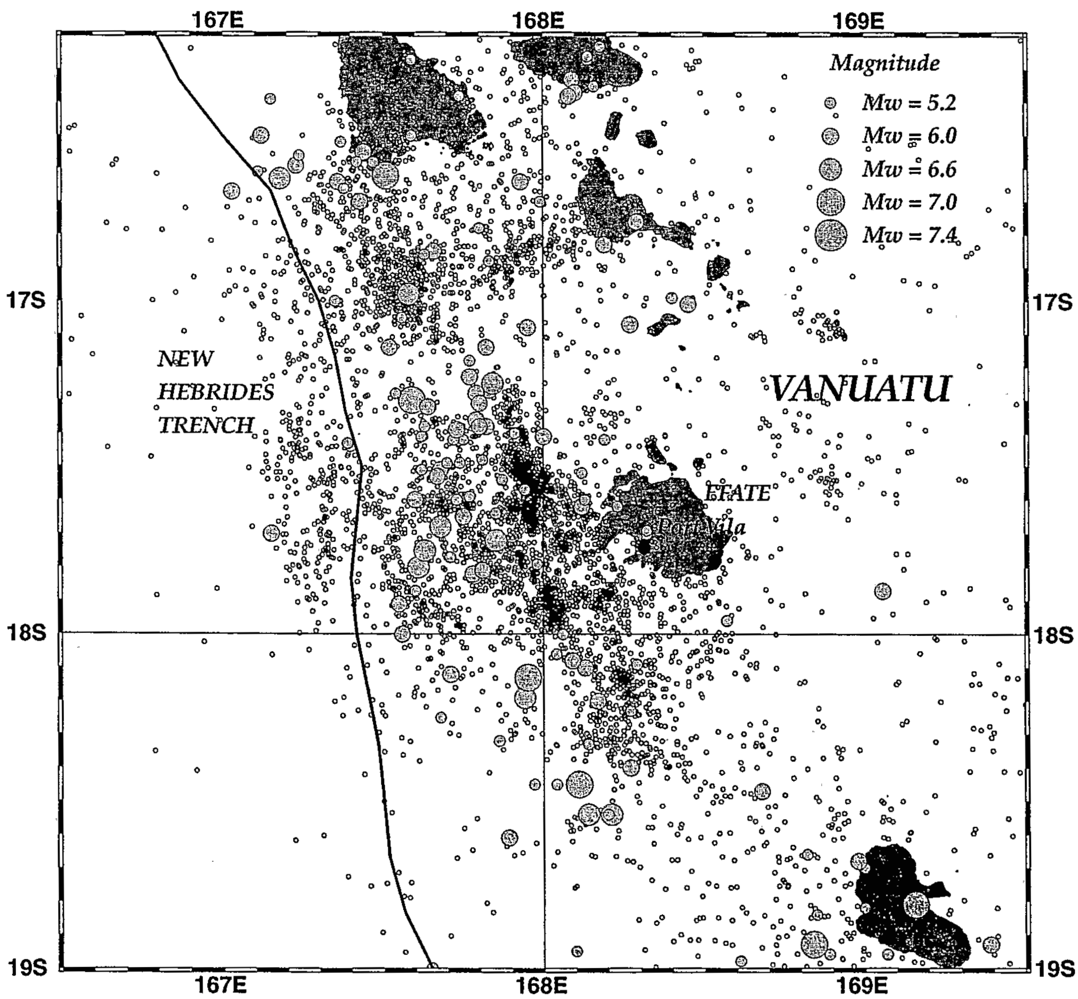

Fig. 1. Earthquake epicenters in the Efate island region. Large dots are epicenters from the Harward CMTS catalog. Small dots are epicenters from the ORSTOM local network catalog.

topographical conditions is a poignant demonstrator of the importance of understanding and assessing site response effects. Some of the most dramatic examples of this phenomenon occurred during the 1985 Mexico City earthquake [e.g. Singh *et al.*, 1988], Armenian (Spitak) earthquake in 1988 [Borcherdt *et al.*, 1989], the Loma Prieta earthquake of 1989 [e.g. Hough *et al.*, 1990], the Northridge earthquake in 1994 and during the recent Hyogo-ken Nanbu (Kobe) earthquake in 1995. A dramatic topographic effect is observed during the Northridge earthquake were ground accelerations as high as 1.8 g have been recorded in Tarzanna near the epicenter.

The geology of Efate island and in particular of the city of Port Vila is fairly simple. Efate is a large Plio-Quaternary volcano-sedimentary island. It is made of prevailingly volcanic eruptive rocks and ashes depots. Its formation has also been controlled by important tectonic uplifts and it is now bounded by large quaternary limestone and sedimentary terraces. The city of Port Vila is located on raised limestone terraces of different ages, up to a height of 120 m. The volcanic substratum does not outcrop in Port Vila area and is probably lying at great depth beneath the city. Active faulting in Port Vila area, roughly in two conjugate directions, has played a major role to control the topography of the city in a blocklike (checker) scheme. The numerous faults have also favored minor, local uplift of blocks. Due to this rough topography, soil thicknesses are very variable within Port Vila area, but are on average, quite thin (few meters). Only at a very few places, significant thickness of soil can be observed. Some of them are man made sedimentary fills. Borehole data usually show, below the thin soil layer, a 20 to 30 meters thick layer of variably weathered limestone banks mixed with sand and gravel depots. To the north of Port Vila, boarded to the west by the Méle bay, one can find a large collapsed zone filled with important (up to several tens of meters) thicknesses of light volcanic sediments. This area, very closed to the city, has the potential for future economical developments, especially around the Bauerfield international airport located in the middle of this distinct geological and pedological unit [Quantin, 1980].

Hence, based on the mapped geology and topography of the city, different locations across Port Vila have the potential of amplifying seismic vibrations. The main objective of this study was to detect site effects in Port Vila, estimate the local site response functions and provide a microzonation map of that phenomenon.

The proper site response functions are best determined from the recorded ground motion during an actual event, preferably, by means of comparison with the recordings at a near-by reference site located on competent ground [see for example; Rogers *et al.*, 1984; Singh *et al.*, 1988; Jarpe *et al.*, 1989; Darrag and Shakal, 1991; Gutierrez and Singh, 1992]. Many investigators, among them Tucker and King [1984], King and Tucker [1984], Jongmanns and Campilo [1993], Liu *et al.* [1992] and Gagnepain-Beyneix *et al.* [1995] evaluated site response functions from weak motions of earthquakes. The implementation of these approaches is quite time consuming, especially for microzoning purposes, even in an active area like Efate island.

A rather fast and inexpensive technique for assessing the site response is the application of microtremor (ambient seismic noise) measurement. This technique has apparently worked well in some areas among them Japan [Ohta *et al.*, 1978], the San Fernando Valley [Kagami *et al.*, 1986], the Dushanbe Valley, Tadjikistan, [Zaslavsky, 1987], Mexico [Lermo *et al.*, 1988; Gutierrez *et al.*, 1992], Italy [e.g. Rovelliet *et al.*, 1991, Hough *et al.*, 1992, Malagnini *et al.*, 1993], New York [Field *et al.*, 1990, 1992], Australia (Gaull *et al.*, 1995], and Israel [Zaslavsky *et al.*, 1994, 1995]. The use of microtremors in estimating site response is gaining popularity. One of the most used techniques has been introduced by Nakamura [1989]. The technique relies on the interpretation of microtremors as Rayleigh waves propagating in single layer over a half-space. Under these conditions the site response function, under linear conditions, is, as a first approximation, the spectral ratio between the horizontal and the vertical components of the seismic motion at the surface:

$$H(w) = \mathrm{Sh}(w)/\mathrm{Sv}(w)$$

where $\mathrm{Sh}(w)$ and $\mathrm{Sv}(w)$ are the amplitude spectra of the horizontal and vertical component of motion, respectively. Results obtained by implementing Nakamura's technique [see for example; Ohamachi *et al.*, 1991; Lermo and Chavez-Garcia, 1993, 1994; Field *et al.*, 1995; Shapira *et al.*, 1994; Gitterman *et al.*, 1995] are in support of the idea that seismic site effects can be estimated by using spectral ratios from only one three-component ($3C$) station.

Although it is well known that soil sites can strongly affect seismic signals, it is commonly assumed that hard-rock sites do not. However, Boore [1973], Davis and West [1973], Tucker *et al.* [1984], Bard and Tucker [1985] and Geli *et al.* [1988] among others, based on theoretical considerations as well as observations, have shown that the site topography can strongly affect the surface ground motions. Investigation of the variation of S-wave motion at several typical sites on outcrops of basement rock on a ridge showed that incident motions are amplified by as a much as a factor of eight over a narrow frequency band. For example, the extensive damage at Canal Beagle, a subdivision of Vina del Mar caused of the 3 March 1985 Chile earthquake, correlates well with the topographical amplification determined from aftershock records [Celebi, 1987].

The use of microtremors in general and the applicability of the Nakamura method in particular is still disputed among researchers (see cited literature above). It is generally agreed that this technique provides a reliable estimation of the resonance frequency for sites where site amplification is significant. Nakamura's method is mainly criticized when implemented for estimating the amplification level. Consequently, as will be described in the following, we tried to match our observations with theoretical site response determinations that are based on modelling the subsurface. In the modelling process, we used available geotechnical (mainly borehole data) and geological data to constrain the ranges of S-wave velocities and the local geological stratigraphy which, in turn, define the site response function.

In this study, the Nakamura method has been implemented for empirical evaluation of site effects in Port Vila that may result either from the subsurface geology and/or the topography. In a few cases, low magnitude earthquakes were also recorded while measuring noise and were also used in the evaluation.

This study deals with identifying areas within Port Vila that may enhance earthquake ground motions and increase the seismic hazard. Site response microzonation of the city is only one aspect in the process of assessing the earthquake hazard in Port Vila. The results presented in this paper are integrated in a comprehensive effort to estimate the site specific, uniform hazard across the city (will be presented separately). Site specific uniform hazard estimations will be preformed by using the SvE method of Shapira and van Eck [1993].

2. The Measurements and Analysis

2.1. *The technique*

Microtremor recordings were made at 100 sites within Port Vila and Bauerfield airport areas. The fieldwork has been carried out using 1 Hz L4C Mark Products seismometers and a 12 bits PC based data acquisition system (see Shapira and Avirav, 1995, 1996). A 12.5 Hz lowpass filter and an 100 Hz sampling rate were selected for recording the data. At each site, the ambient noise was recorded for 3 minutes every 10 minutes during one hour. The recorded microtremors were analyzed by the GII-SRD program, using the Nakamura [1989] technique to recover the polarization characteristics of the wavefield. That involves computing the ratio of the spectra of both horizontal components relative to the vertical component of ground motion. For each site, average vertical and horizontal spectra are computed from several 20 seconds data samples. The spectral ratios for both horizontal components are then computed. Finally an average spectral ratio is computed.

2.2. *Observations-typical examples*

On Fig. 2 are plotted 25 individual site response functions (i.e. spectral ratios of the horizontal over the vertical components) from sites throughout Port Vila. Sixty percent of the sites surveyed exhibit similar site responses. It actually shows no amplification at frequencies up to 10 Hz. Around 10 Hz in the spectrum, one can see some scattering due to small variations in soil layer thickness.

If we adhere to the basic assumptions upon which the Nakamura method is based then, as a first approximation, the resonance frequency, $\mathbf{f0}$, of the superficial layer and the amplification level $\mathbf{A(f0)}$, are given by the equations:

$$\mathbf{f0} = \mathbf{V_1/4H}$$

$$\mathbf{A(f0)} = \mathbf{V_2 * r_2/V_1 * r_1}$$

where $\mathbf{V_1}$ and $\mathbf{V_2}$ are the *S*-wave velocities in the upper layer and the bedrock, respectively. The corresponding densities of the material are $\mathbf{r_1}$ and $\mathbf{r_2}$, and $\mathbf{H}$ is

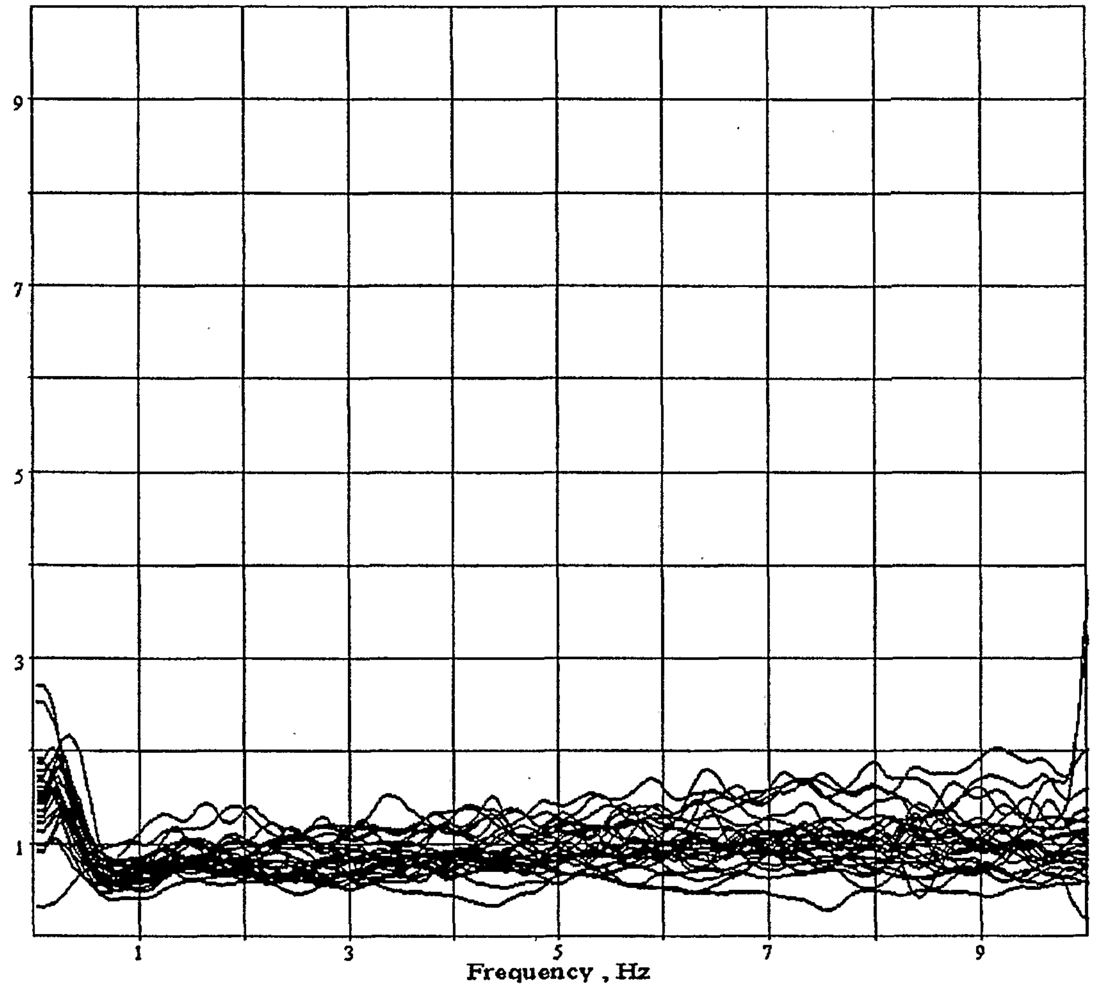

Fig. 2. Spectral ratios of sites throughout Port Vila with no resonance effect.

the thickness of the superficial layer. Consequently, the capability to identify significant site effect is heavily dependent on the impedance at its subsurface (practically V_2/V_1). At this stage we should add that the Nakamura technique is basically associated with ambient noise measurements, however, as shown by Lachet and Bard [1994], Zaslavsky *et al.* [1994], spectral ratios of incident S-waves from earthquakes yield similar results as those obtained from noise measurements.

As demonstrated in the examples shown in Fig. 2, there is no significant site effect among the investigated sites. These observations are confirmed by analyzing the recordings of 3 earthquakes that happen to occur during the occupation of the sites. The spectral ratios of the S-wave recordings (Fig. 3) suggest that some resonance at lower frequencies might be associated with deeper layer(s) of higher S-wave velocity. Nevertheless, the amplification is still low with no significant influence on the seismic hazard at those investigated sites. Figures 4 and 5 show the evaluated response functions of two areas of Port Vila with slight amplification,

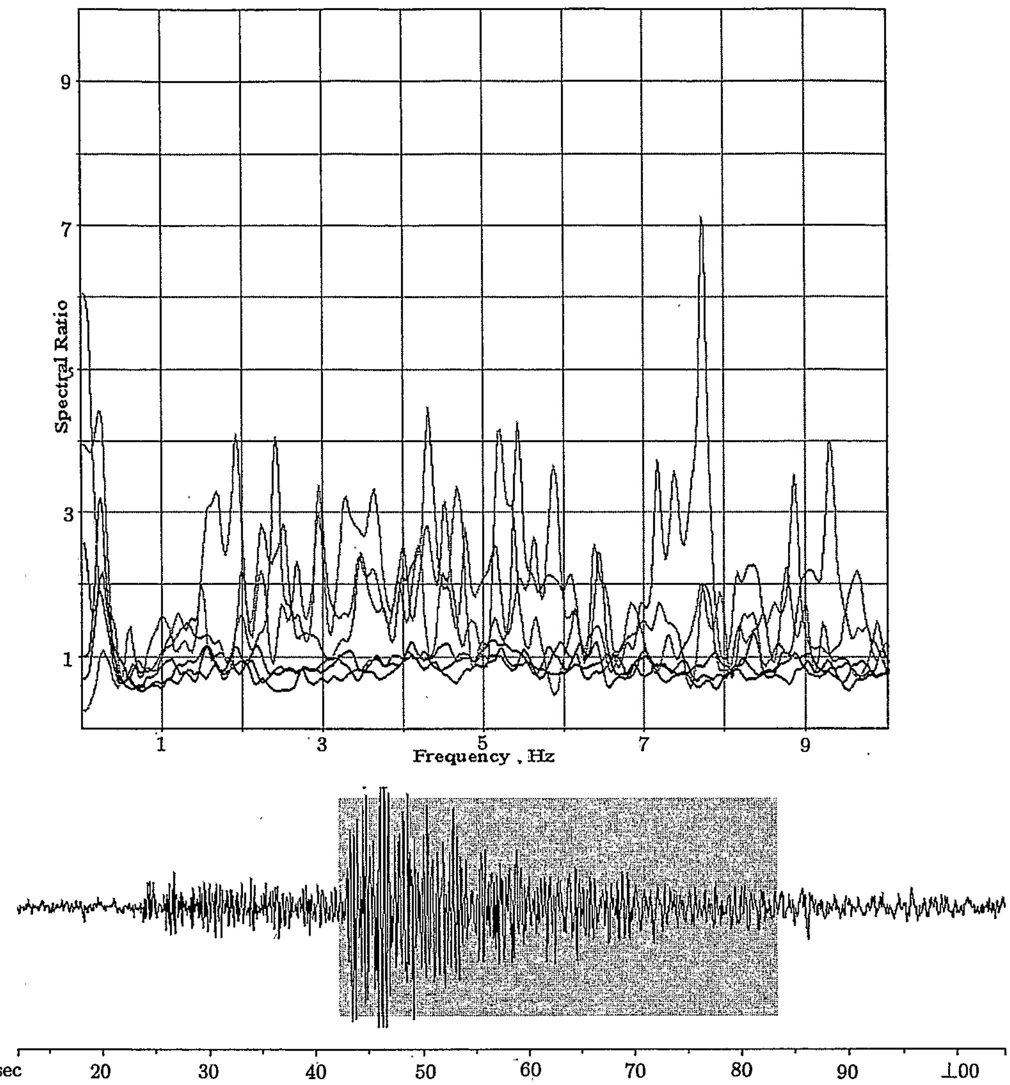

Fig. 3. Comparison of spectral ratios at three sites computed with microtremor (black curves) and S-wave coda (grey curves). The grey box on the seismogram shows the time window of the signal used to compute the spectral ratio.

within a factor of 3, over a broad range of frequencies. One (Fig. 4) is a compilation of the responses in reclaimed land located in the harbor area [Ardimani and Star wharf] and in the downtown area, at three sites along the sea front. There is not a single distinguished peak of resonance but rather a broad dome-shaped zone of amplification centered at 4 Hz. In both areas the surface of the reclaimed land is fairly small and the maximum thickness of the fill is of the order of 5 meters at the sea front area and up to about 10 meters at the wharf platforms. Hence, for f0 = 3–5 Hz. And assuming a shear wave velocity of 100 m/s for the gravel [Fah *et al.*, 1997] used to made up the platform over the bedrock (modern reef flat), we get estimated thicknesses of 5–8 meters that are compatible with the observed ones.

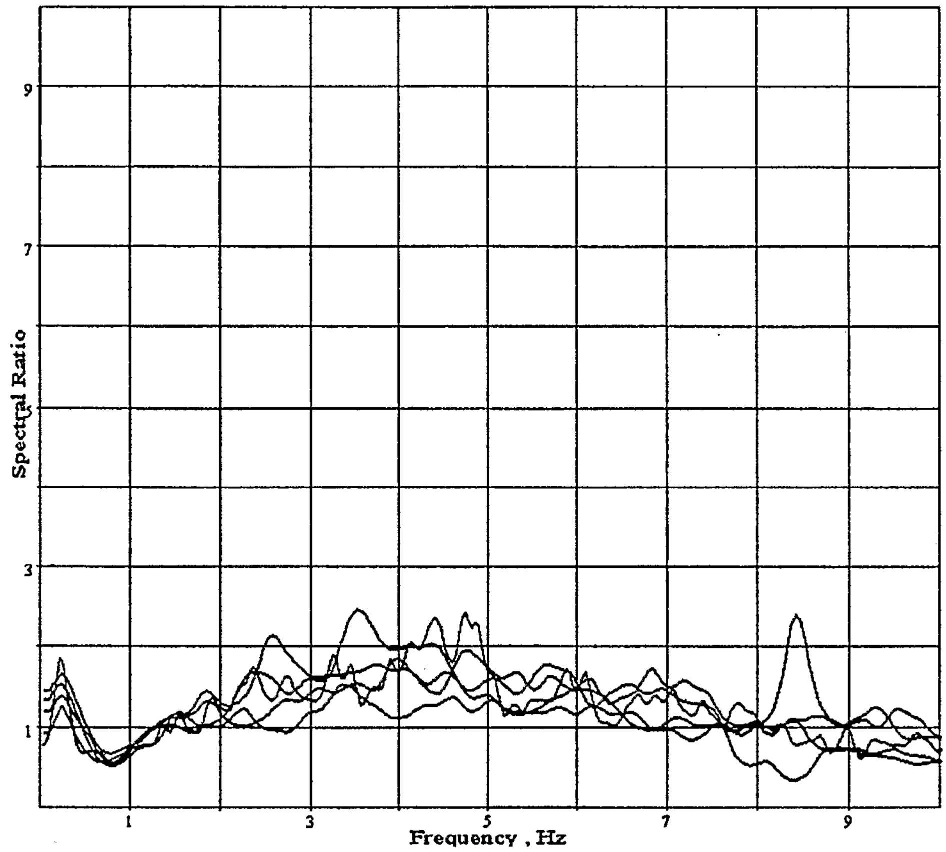

Fig. 4. Spectral ratio of sites located on reclaimed areas.

The Tassiriki area around the bend between the two inland lagoons, shows a slightly different response (see Fig. 5). This is a flat and sediment filled area and it is probably at the junction of majors faults, now inactive, that made up the troughs where the lagoons are located. The maximum amplitude of the ratio is variable, between 2 and 3, and its position spreads between 5 and 7 Hz. Assuming again a low shear wave velocity between 100 and 200 m/s, this yields a top layer thickness of about 10 meters.

Figure 6 is an example of the response at a site of man made fill located along the main street to the airport at the northern limit of the city. This location has been used for a long time as a dumpsite. Its resonance frequency is centered around 2.5 Hz with an amplification factor of about 6. Assuming S-wave velocity of the upper layer to be between 100 and 200 m/s, may suggest a layer thickness of 10 to 20 meters. This figure is reasonable, yet not confirmed by other geological or geophysical information. The observed amplification factor at this site is not representative of site responses in Port Vila. It is located in a trough that was probably already partly filled with alluvium. This is usually the case in many other throughs that have been surveyed during this project. In general, the responses of sites located at the bottom of such throughs show a slightly higher site amplification

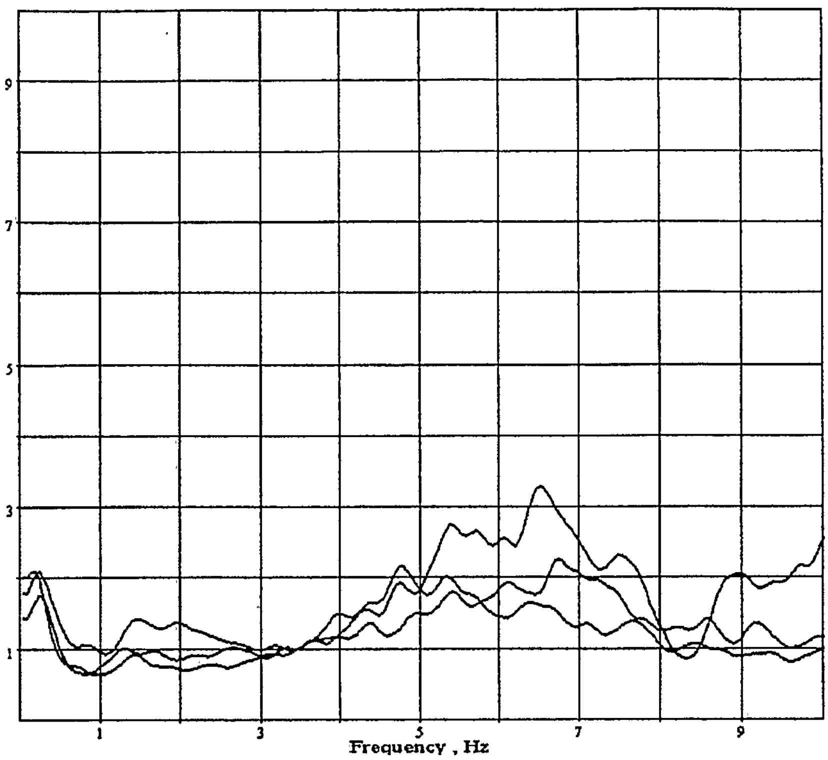

Fig. 5. Spectral ratio of sites located in the Tassiriki area.

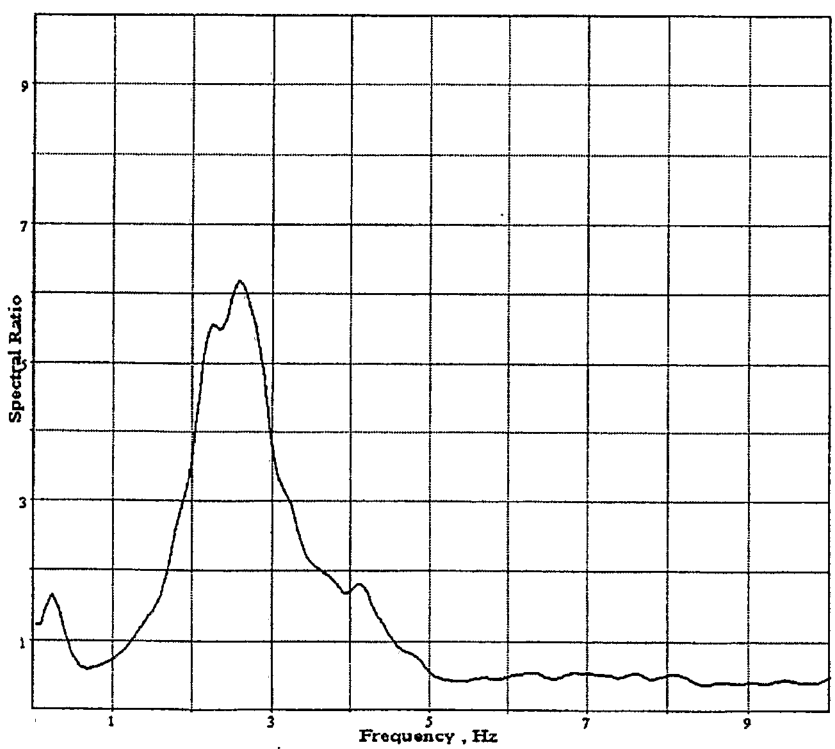

Fig. 6. Spectral ratio of the site nb 50 located on an old dump zone. (Le depotoire)

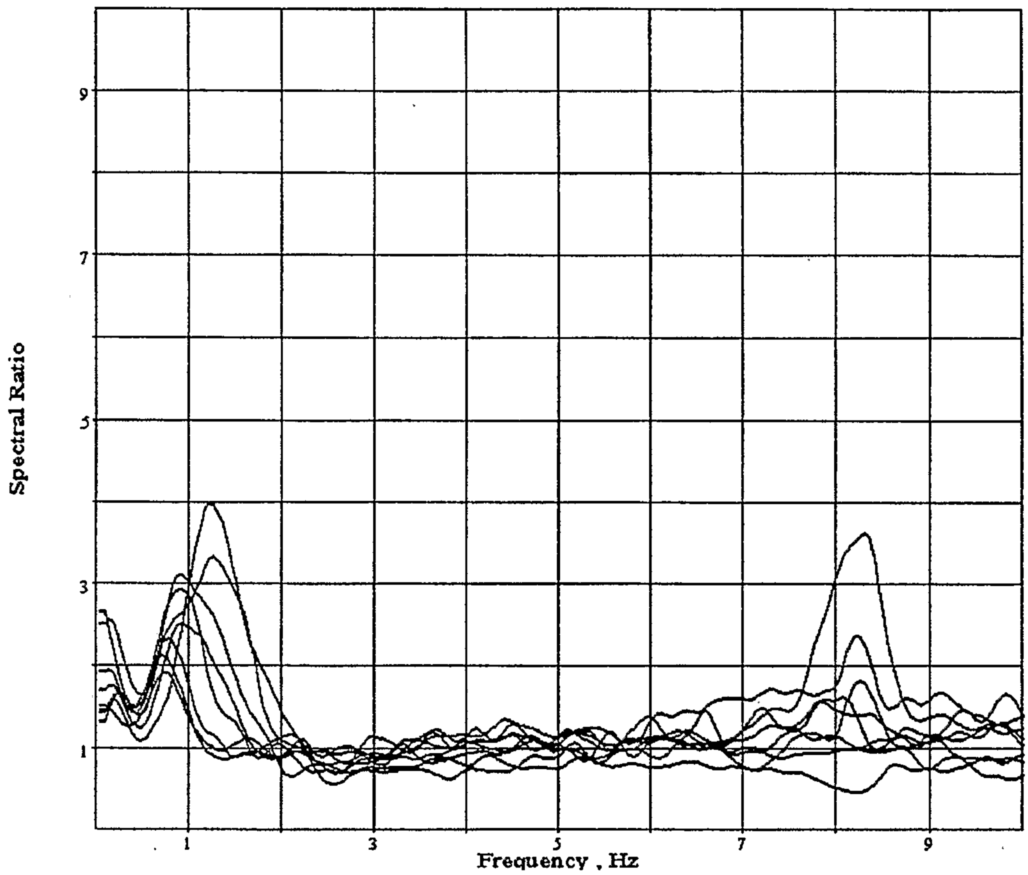

Fig. 7. Spectral ratios of sites located on Méle terrace, around Bauerfield airport.

of a factor of about 2 to 3 at frequencies between 5 and 10 Hz as compared to most sites across Port Vila.

The area around Bauerfield airport, north of Port Vila is part of the larger Méle terrace. The response functions obtained for that area (see Fig. 7) are characterized by two peaks, one at low frequencies around 1 Hz, and one at higher frequencies between 8 and 9 Hz. The peak at low frequencies is systematically observed at each site, but with a variation in position and amplitude, which is indicative of varying thickness of the superficial layer. Assuming a constant shear wave velocity (100–200 m/sec) over the considered area, that implies a thickness variation between 20–100 meters. The second pick centered at 8.2 Hz is not observed on all sites from the Bauerfield airport area. It could be related to a sand layer which is observed in many places in this area up to the base of Mt Bernier that limits the Méle volcano-sedimentary terrace to the north.

3. Site Response Microzonation

Based on these observations, the soil map [Quantin, 1980], the topographic map [I.G.N., 1968] and drillhole information provided by the Geology and Mines

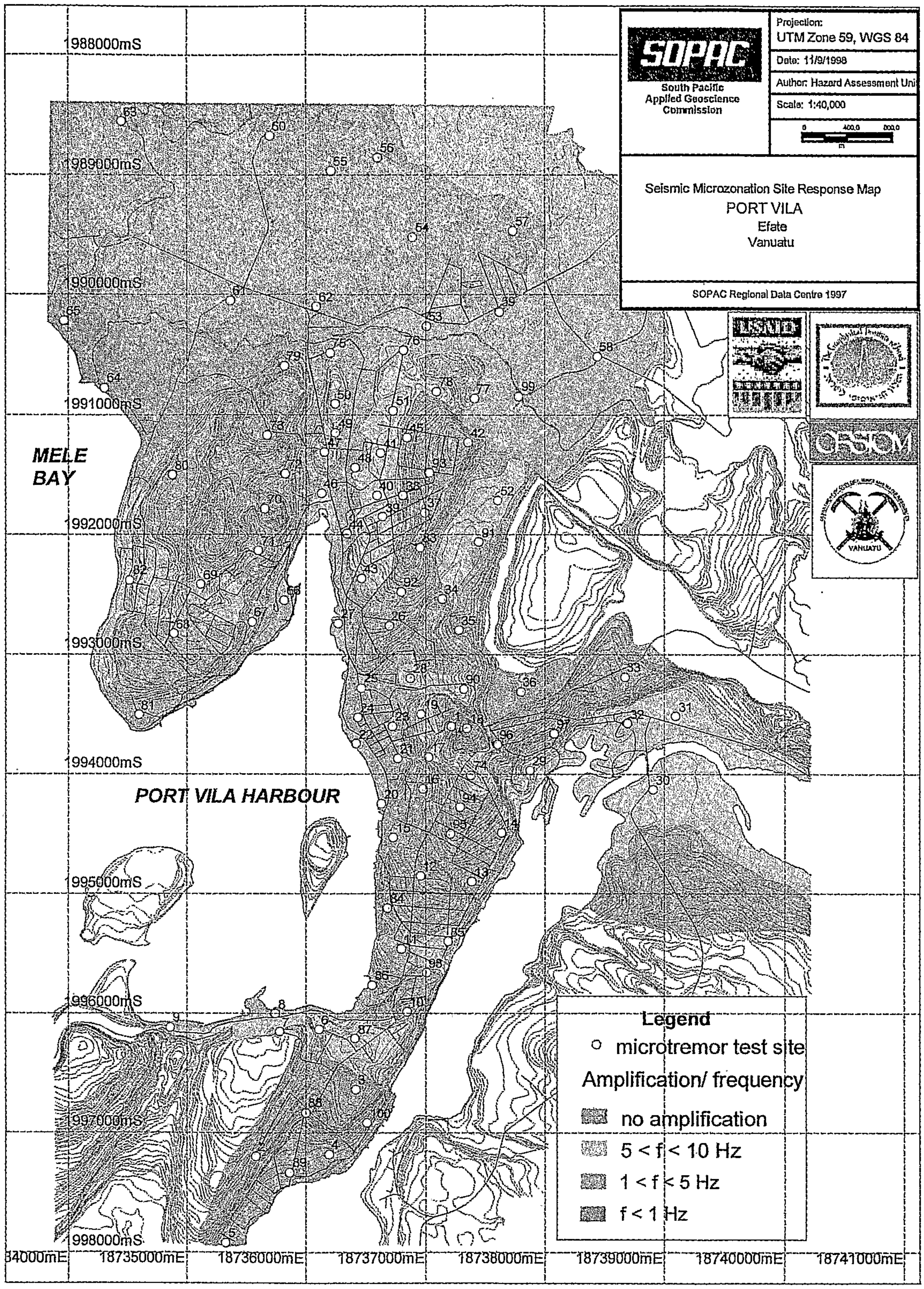

Fig. 8. Microzonation map of Port Vila.

department of Vanuatu, we have prepared a zoning map of the Port Vila and Bauerfield airport areas (Fig. 8). We have also modelled the subsurface at some sites when the amplification site factor was above 2. The modelling process is based on matching the observed response functions with an analytical function that is calculated by assuming S-wave velocities, densities and thicknesses of the layers underlying the surface. The computations associated with each model are made by using the program of Joyner [1977]. The observed site response parameters and computed model parameters across Port that provide similar analytical functions are presented in Table 1. The fitting between the observed and the analytical functions is made using eye-ball techniques. The two functions should match accurately the resonance frequency while the matching of the amplification levels is achieved with a tolerance of about 10%. The S-wave velocities are assumed, based on general geotechnical information that is associated with the type of rocks and soils in the south Pacific Islands [G. Shorten, SOPAC, Private communication]. Under those assumptions we have matched the layer's thickness to yield the observed resonance frequency.

Based on the analysis of the observed site responses, it is suggested that Port Vila and the Bauerfield airport areas are divided into a 4 zones system, each of them characterized by a predominant resonance frequency and a range of expected site amplification factor. A site with no amplification factor would not be included in either zone, no matter the shape of the spectral ratio function. To a first approximation, the relationship between the height of a building and its fundamental period of vibration can be expressed by the crude formula:

$$\mathbf{T = (nb.\ storeys)/10}$$

Two groups of buildings are then considered for the map: low rise (1 to 5 storeys) and high rise (more then 5 storeys) building. If the natural period of the ground matches the period of the building, then resonance may occur and may increase

Table 1. Site response observations and generalized estimations.

Observed				Estimated by Modelling	
Site No.	Sites Name	Resonance Freq. (Hz)	Amp. Factor	H (m) Sediment Thickness	V (m/s) Shear Wave Velocity
8	Ardimani wharf	4	3	15	200
29	Tassiriki	5–7	3	5–7	120
50	Dépotoire	2	6	10	100
57	Bauerfield	1.2	4	25	120
74	Ecole française	9	3.5	2.5	100
78	Olhen fresh wind	7	4	3.5	100
82	Malopoa	8	3.2	3.8	110

the probability of damage to the building. We should emphasise that this is only a rough estimation and that actual measurements should be performed to verify the resonance frequencies of the different types of buildings in Port Vila.

The four zones on the map are as follows:

Zone 1. No site resonance: limestone terraces with no or little topographic variations.

Zone 2. Low resonance frequencies (< 1 Hz): thick sedimentary layer. Found only in Bauerfield area. Possible resonance for very high rise building (more than 10 storeys).

Zone 3. Resonance frequency between 1 and 5 Hz. Found in the reclaimed areas and in a transition zone between Bauerfield area and Port Vila. Possible resonance for medium to high rise building (5 to 10 storeys).

Zone 4. Resonance frequency between 5 and 10 Hz. Found in some areas with shallow sediments (up to few meters) over limestone basement or areas with complex topography (cliff, narrow graben, ...). Possible resonance for low rise building (1 to 5 storeys, most frequently found in Port Vila area).

4. Discussion

This extensive study was aimed mainly for identifying locations within Port Vila, Vanuatu that may exhibit unusual site effects during strong earthquakes. We have applied the Nakamura method over 100 sites across Port Vila and obtained rough estimations of the resonance frequencies and amplifications of the superficial layers. The Nakamura [1989] approach, based on seismic noise measurements, has gained great popularity and is used by many across the globe. However, it is by now well known that this approach may fail at locations where amplification effects are only marginal. Even when a strong amplification is observed, the amplification factor is often not accurately determined and should be substantiated with additional geological and/or geophysical information.

Except of few areas within Port Vila, that exhibit amplification effect of engineering significance, most of the city area seems not to be vulnerable to site effects which may result either from soft sediments overlying hard rocks or from the topography. Despite the limitations inherent in the measurements and their interpretations, we may fairly assume that significant amplifications (let us say with factors greater than 2), if exist, would have been detected. For example, the map in the down town area, shows no resonance pattern associated with areas close to the coast, where eventually soft materials can accumulate. However this is perhaps not true along the second lagoon outside the map where strong ground shaking are reported during earthquake. We also did not often observed significant effects due to the topography in the site responses, up to 10 Hz. The only sites where such large effects have been observed are located on the highest points in the city. Above 10 Hz, the complexity of the spectral ratio at some sites located on rocks could also indicate topographic effects. However building cannot be affected very much by resonance in this high frequency band.

Earthquakes are felt frequently in Port Vila. Surprisingly, there are very few cases of reported damage to buildings [Louat and Baldassari, 1989] over approximately a 100 years period. As an example, the July 15, 1981, Ms 7 earthquake occurred at about 80 km, northwest of Port Vila and did not generate much damage. There is also no reported dramatic site effect across Port Vila but there are few places where earthquakes are more strongly felt than elsewhere. These locations are coincident on the map with zones characterized by a resonance frequency. One location is along the road to Méle and is within the "Bauerfield zone" with resonances around or below 1 Hz. This is the present location of the glass depot PAF. They have reportedly noted anomalous glass breaking during earthquakes. Other places that experienced stronger shaking spread along the shore of the second lagoon, starting from the Tassiriki area (narrow zone that connect the two inland lagoons) which is characterized by a resonance frequency between 5 and 10 Hz, affecting mostly low rise buildings. It is clear, in both cases, that the strong shaking experienced at these locations was site dependent ground motion amplification.

In conclusion, sites in Port Vila usually show no significant site effects. This is due to the poor sedimentary cover found on recent volcanic structures located on modern island arcs like the New Hebrides. In most places in the city, large thicknesses of uplifted limestone terraces are found on top of the volcanic rocks and ashes depots which yields no site effect. Both topographical effects and very localized soil thickness controlled by active faulting can in some places, increase site amplification factors.

We should reiterate that the site response functions that were discussed in this study are associated with weak motions at the range where the behavior of the soils is linear. In this respect, the site response functions do not represent the site effects under strong ground motions that may cause the material (soils) to behave nonlinearly. The nonlinear characteristics of different sites within Port Vila are currently beyond the scope of this study. Based on the results presented in the above, nonlinear site response can be determined analytically and these are included in the SvE method of Shapira and van Eck [1993] for estimating seismic hazards in Port Vila, Vanuatu.

Acknowledgements

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