Response Spectra for Selected Papua New Guinea Accelerograph Records

McCue, K.[1], Sinadinovski C.[2] and Pekevski, L. [3]

[1] Central Queensland University, Rockhampton Qld, Australia,
[2] Global Seismics, ACT, Australia,
[3] former Director of the Seismological Observatory, Skopje, Macedonia.

Abstract

Strong motion recordings of near-field earthquakes in Hela and East New Britain Provinces, Papua New Guinea are analysed to understand the earthquakes and to provide input into building code development. Spectra for earthquakes in the Tari region in Hela Province (2018), and Rabaul (2019) and Warangoi (1978) East New Britain Province are shown for the first time. The recent earthquakes were recorded digitally and continuously at 200samples/s but at Warangoi, the ground shaking was recorded on a triggered analogue SMA-1 Kinemetrics recorder and the 70mm film record has been re-digitized for this study.

The magnitudes of the earthquakes were 5.8, 6.1, 6.3 and 7.5 with nearest source distances of 20 to 50km. Calculation were made over a wide frequency range and the majority of the spectral peaks were between 0.1 and 0.8 sec. The maximum spectral acceleration, at Rabaul during the 2019 M7.5 earthquake, is 2.7g and the width of the flat section of the spectra are magnitude dependent and may also be a function of the regional geology and source mechanism.

The spectra are recommended for design in Papua New Guinea, replacing the current code spectra for normal foundations, not crystalline rock or soft soils. The results obtained in this study are important for refining Building Codes in Papua New Guinea in particular, as well as other countries in the Southwest Pacific.

INTRODUCTION

Papua New Guinea (PNG) is one of the most active countries on Earth in terms of earthquakes and active volcanoes as measured by the velocity of the colliding tectonic plates there. The need to design engineered structures and buildings in PNG to survive earthquakes was reinforced in February 2018 when a major magnitude 7.5 earthquake and thousands of aftershocks, six of them of magnitude 6 or more, struck the Southern Highlands, Hela Province in particular and its capital Tari. Hela province is the centre of PNG's oil and gas production which, as a result of damage to the camps and equipment, was forced to shut down for months.

How strong was the ground shaking, how long did it last and what was the frequency range of strong shaking? These questions and the similar one - what ground shaking should buildings in PNG be designed to resist are the objects of our interest. Until now there have been few recordings of strong ground shaking in PNG though some equipment has been installed since 1967 to do that. Very few useful records were subsequently obtained, partly because there were just a few recorders, partly because the equipment was not designed to operate in the heat and humidity of tropical regions and partly because PNG is a large mountainous country and expensive and difficult to get around. Even then, when analogue accelerograms were recorded (Figure 1), having them processed (digitised) to be useful was a daunting exercise. A history and table of peak ground acceleration (pga) recorded is listed by Ripper (1992).

Some engineers simply adopted building codes used in California or New Zealand where the plate collision rates are 1/3 that of parts of PNG. These buildings will perform better than those not designed for vigorous ground shaking but may not survive the higher than-designed-for shake.

In 1982 a revised Earthquake Building Code for PNG was introduced (Jury and others, 1982) and this summarised requirements for design and construction, adopting the then-current NZ Code with different zone factors to account for the variability of hazard across PNG.

Specialist studies such as by Anton et al, (2010) have recommended response spectra for particular sites, in their study for use in Port Moresby, the capital where rapid unprecedented development has occurred over recent decades and hazard is relatively low.

HISTORICAL MEASURES OF STRONG SHAKING IN PAPUA NEW GUINEA

Prior to the development of accelerographs, the intensity of shaking assessed against various scales such as the Mercalli, Rossi-Forel or similar scales based on felt effects and damage were used to indicate the relative amplitude and attenuation of ground shaking. Hundreds of isoseismal maps have been drawn up for PNG earthquakes based on the Modified Mercalli Scale, but intensity being subjective and descriptive is not easily incorporated into design.

Early analogue accelerographs were installed in PNG at the Bougainville Copper mine, Panguna Bougainville and at Yonki Dam Site in the Eastern Highlands Province in 1967, at Lae Unitech in 1968, Musa Dam Site in Central Province in 1972 and Kandrian West New Britain in 1975. A few earthquake records were subsequently obtained and analysed by Boyce (1970), Denham et al., 1973, Gaull (1976) and McCue (1979, 1980 and 1981). The digital data have subsequently been lost.

East New Britain Province

A shallow magnitude 5.8 earthquake was recorded on an SMA-1 accelerograph near the Warangoi Dam site 60km SE Rabaul on 3 December 1978. The first 16s of the record was hand digitised at the time (McCue, 1981), the pga 0.125g and pgv ~7 cm/s. The digital strong motion data files and database have not survived the many computer upgrades and personnel in Port Moresby, but the film record was saved.

An isoseismal map was prepared by Observatory staff who rated the intensity in the sparsely populated epicentral region at least MM6 (Figure 3) and it was felt out to about 250km., as far as Kavieng at the northern end of New Ireland, but infrastructure and buildings were few and far apart. An earthquake of this size in Australia such as that near the relatively densely populated city of Newcastle in December 1989, was felt over at least five times the area of that at Warangoi and the maximum intensity was assessed at about MM8 over a small area. Obviously the upper crust in New Britain and New Ireland is very attenuative compared with that in the Sydney Basin.

Reinterpretation of the 1978 Warangoi Accelerogram. The first 16 seconds of the SMA-1 recorded accelerogram (Fig. 1) was re-digitised at Skopje Observatory and put through routine processing. Allowing for the minimum 0.1sec startup time the S-P time is about 2 sec corresponding to an epicentral distance of about 20km. The Response Spectrum is shown in Figure 3.

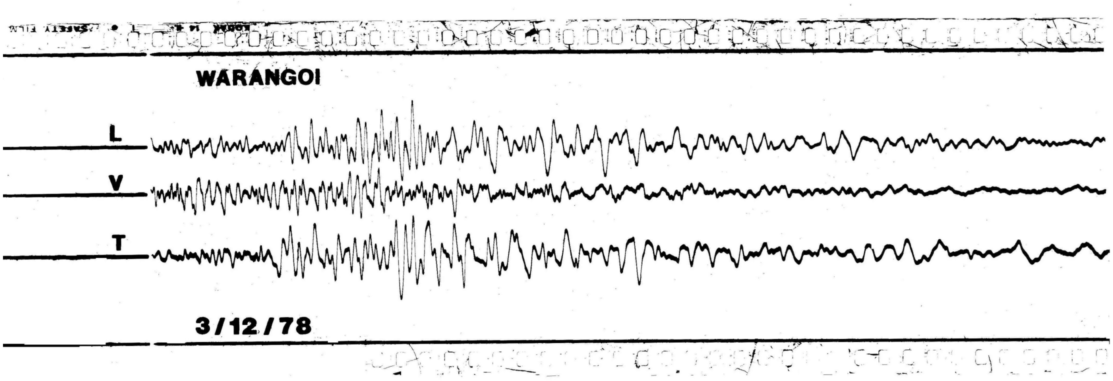


Figure 1 The SMA-1 recording of a magnitude M5.8 earthquake within 20km of the proposed Warangoi Dam site 60km SE of Rabaul in East New Britain. Note the lack of time marks which mysteriously resumed seconds beyond the cutoff for digitisation. The film is 70mm wide, the translation rate 10mm/sec. The instrument is supposed to trigger within 0.1s and L,V and T are the longitudinal (north), vertical and transverse (east) components respectively.

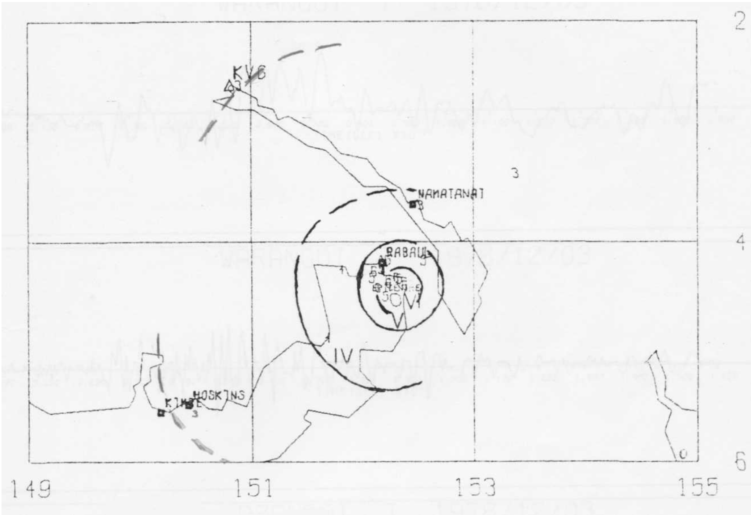


Figure 2 Isoseismal Map of the M5.8 Warangoi ENBP earthquake, 3 Dec 1978.

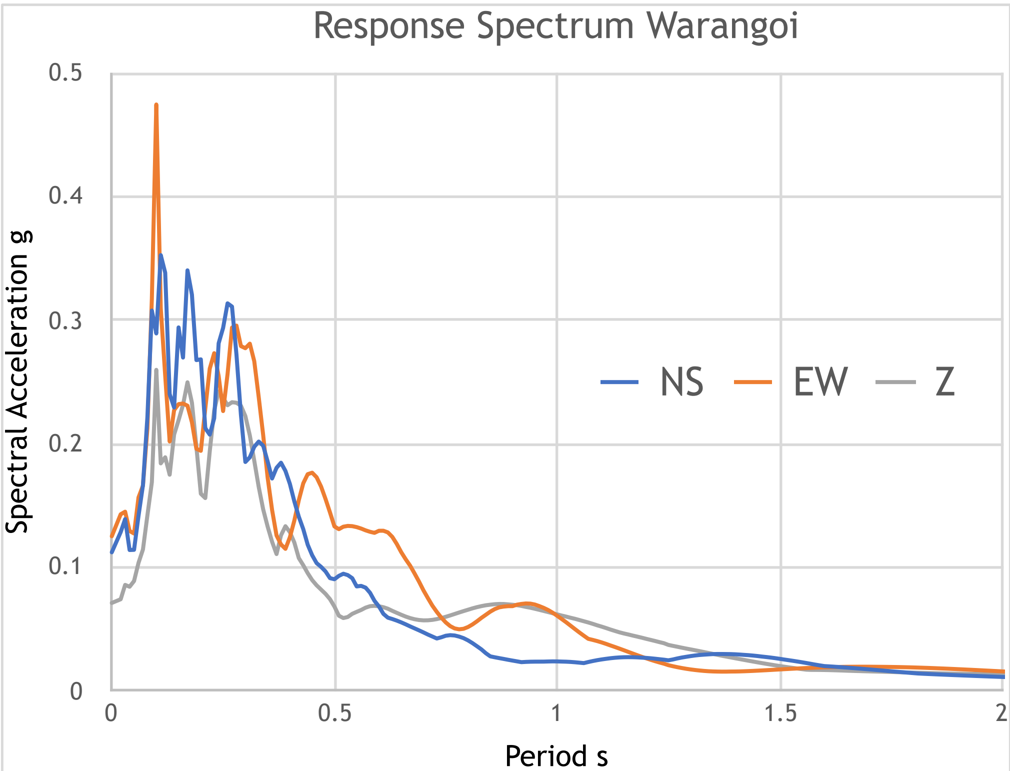


Figure 3 Response Spectrum Warangoi Dam Site ENBP, 3 December 1978. The vertical component Z (grey/green) is about half the horizontal response to 0.6s period.

Bougainville. A magnitude 7.6 earthquake on 18 March 1983 off southern New Ireland triggered several accelerographs including one on rock on the 460 Bench in the BCL mine at Panguna. It was strongly felt at Panguna and Arawa but did no damage, intensity MM5 at the mine site. The distance was about 200km and the focal depth about 90km a useful comparison with later earthquakes. The pga at 200km was about 0.03g and the response spectrum is quite peaked to 0.5g in the 0-0.4s period range (Sarma in McCue, 1984 and Silverstein et al, 1986).

RECENT DIGITAL STRONG MOTION RECORDINGS

Southern Highlands. A magnitude 7.5 earthquake struck Hela, Southern Highlands, Western Highlands and Enga Provinces of Papua New Guinea on 26 February 2018 causing more than 160 deaths, numerous injuries and huge landslides that destroyed native gardens and fish stocks in the rivers and closed down the oil and gas industry there (McCue, Gibson and Love, 2018; Gibson, McCue and Love, 2018). There were no strong motion recorders in the epicentral area at the time of the main shock and the first five of six large aftershocks.

From 19 to 23 March a six-station accelerograph network (Table 1) was rolled out over a 100km length of the fault zone in the epicentral region of the mainshock (Figure 4). Thousands of aftershocks were recorded at 200 samples/second continuously with GPS timing. Data were recorded on SD cards on site. The last large aftershock of the sequence, magnitude 6.3, occurred on 7 April and was recorded on all 6 stations. The horizontal peak ground acceleration (pga) at right angles to the strike of the mainshock was in excess of 0.67g at a distance of 35km and strong shaking lasted more than 10 seconds.

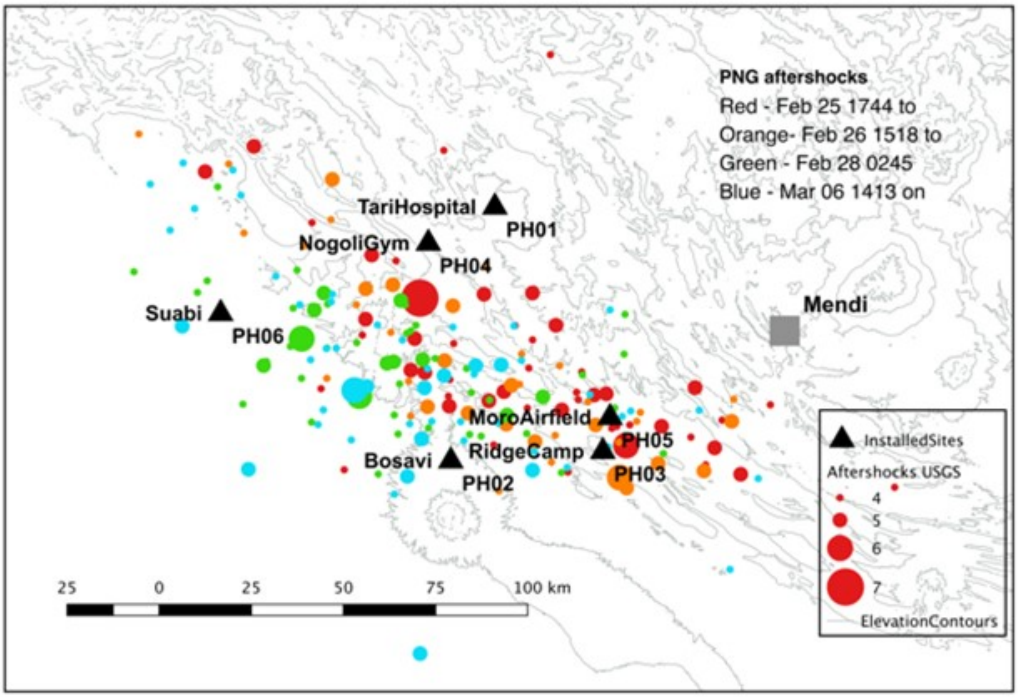


Figure 4 The aftershock monitoring network in Hela Province, March and April 2018. The accelerographs are at sites marked with a black triangle, their 4-letter site codes also shown (PH01 to PH06).

All but stations PH02 and PH06 are at ~2000m altitude on a 3km thick uplifted limestone sequence. Bosavi (PH02) is on outwash from a large intraplate shield volcano while Suabi sits on thick sediments overlaying thinned continental crust. The depth to Moho has not been measured.

Table 1 Hela Province Accelerograph Codes and Site Names

Station Code	Site
PH01	Tari Hospital
PH02	Bosavi Village
PH03	Ridge Camp
PH04	Nogoli Village
PH05	Moro Airstrip
PH06	Suabi Village

Not surprisingly, the accelerograms exhibit considerable complexity, the P wave arrival mostly clear but the S wave arrival time is difficult to identify. The ground motion is often dominated by large Love waves, strong horizontal long-period ground motion and little corresponding vertical shaking, as shown in Figure 5.

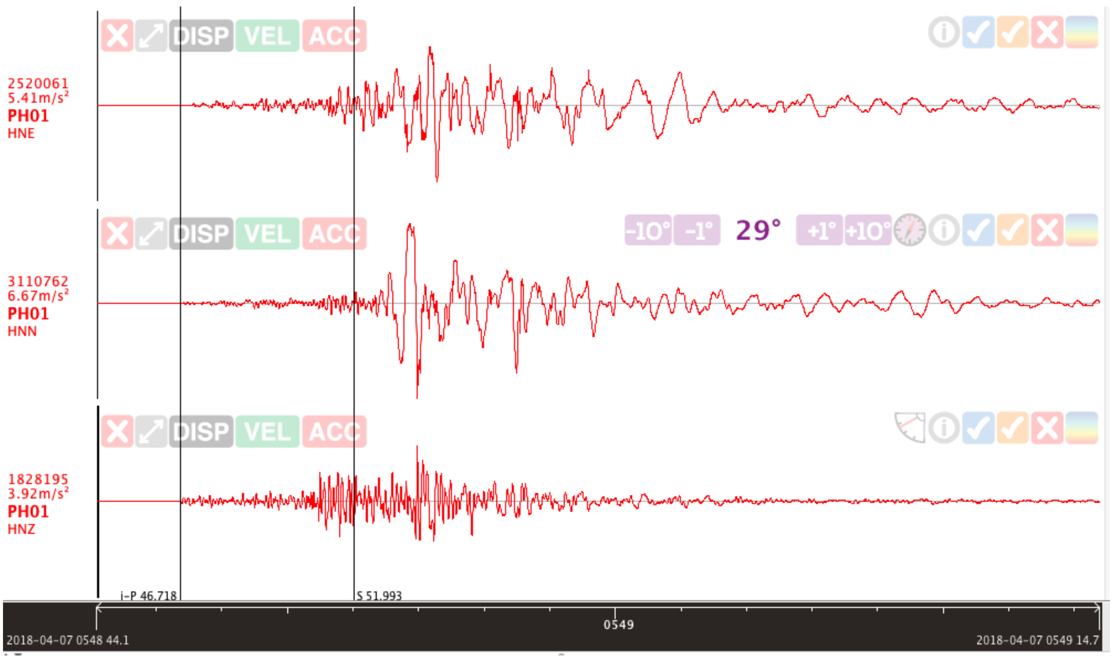


Figure 5 A record of the ground acceleration at Tari Hospital during the large M6.3 aftershock on 7 April 2018 rotated 29° clockwise to the direction of maximum ground shaking (perpendicular to the strike of the faulting).

More than 120 aftershocks have been located (McCue and others, 2018), the P and S arrival times then used in a tomographic inversion to investigate variations in the assumed crustal model, an iteration on the way to improving the locations.

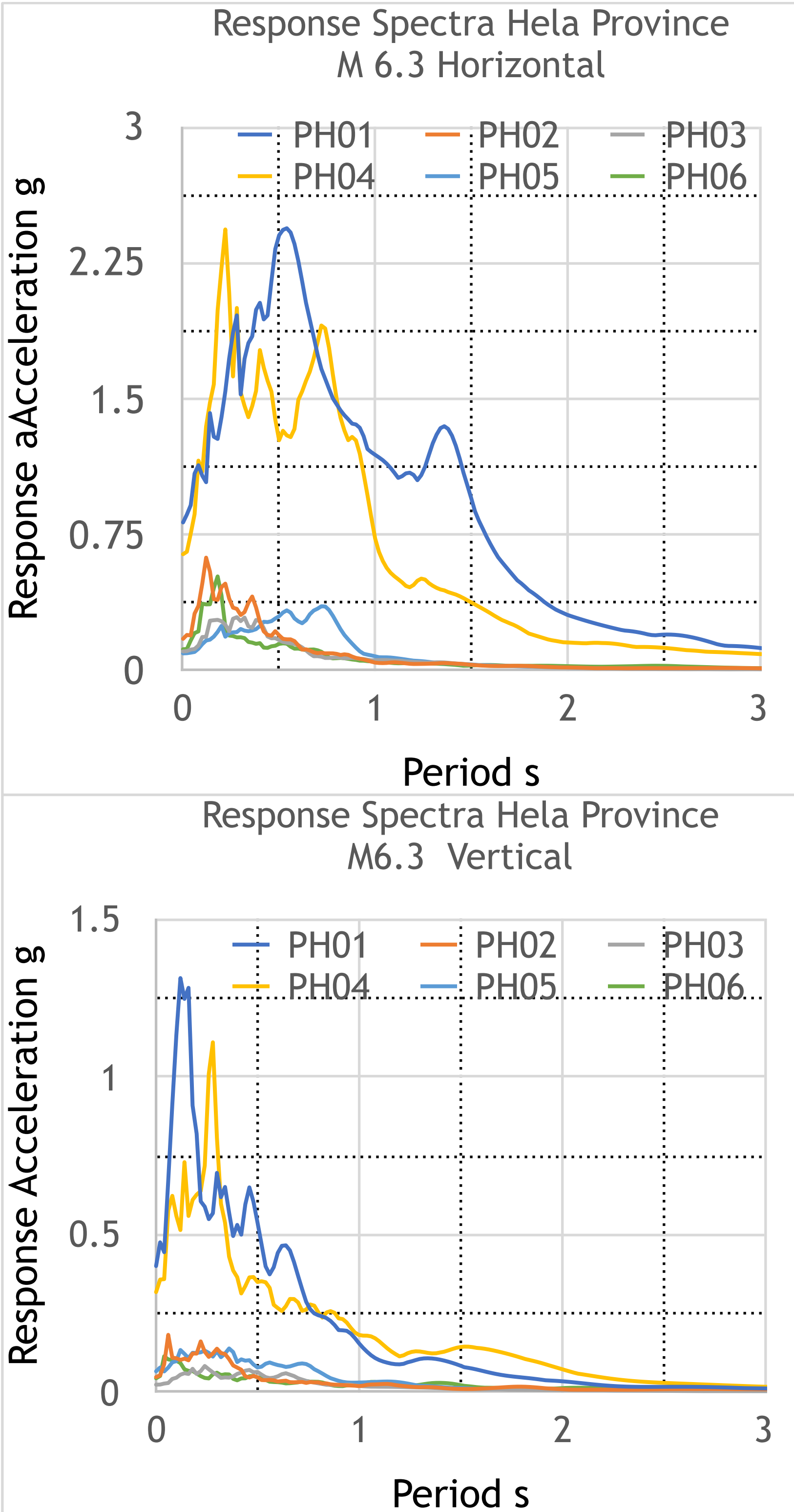


Figure 6 Response spectra for the resultant horizontal (top) and vertical acceleration.

Response spectra for the resultant horizontal and, separately, vertical acceleration are presented in Figure 6. All the spectra plateau from about 0.3 to 0.8s period and the spectral accelerations of the two closest, about 30km from the source, at Tari (PH01) and Nogoli (PH04), are an order of magnitude greater then the other spectra at about 100km from the source. This highlights the rapid attention of shaking from the source first noticed with PNG isoseismal maps when compared with Australian earthquakes.

Horizontals The Tari and Nogoli spectra are similar, like their gross geology, with an interesting second peak at about 1.2 to 1.3s. This may correspond to the thin limestone layer (H=ST/4) where H is the thickness (km), S the shear wave velocity (km/s) and T the period (s). With S~2.5km/s, H=800m.

Vertical The vertical amplitude of shaking is considerably lower than the horizontal amplitude, not unexpected given the layer cake like geology with strong Love waves evident on the accelerograms. The spectrum is also much narrower with peaks at 0.15 to 0.25s.

Surprisingly there in no obvious sign of the deep sediments under Suabi nor of the major volcano under Mount Bosavi although a seismic wave velocity contrast is evident in the tomographic results (Sinadinovski and others, 2019). Contrast that with the two neighbouring sites at Moro and The Ridge which show quite a different response to each other.

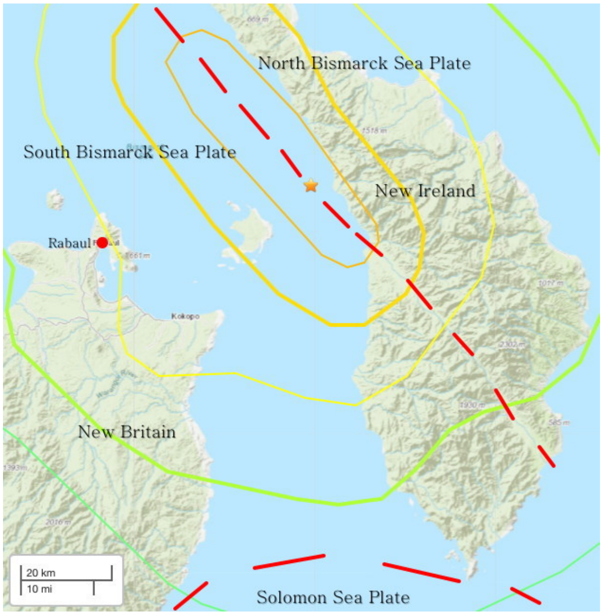


Figure 7 Plate tectonic setting of Rabaul with the marked epicentre of the 2019 M7.5 earthquake and plate boundaries (red dashed lines).

Major Earthquake New Britain and New Ireland. Rabaul, the capital of East New Britain Province, has the highest earthquake and volcanic hazard of any town or city in Papua New Guinea due to its tectonic setting near three plates and their high rate of relative plate movements (Figure 7).

In 1971 there were two near magnitude 8 earthquakes south of Rabaul along the subducting edge of the Solomon Sea Plate. No accelerograph data were recorded at the time.

On 17 May 2019 a major magnitude 7.5 earthquake occurred along a transform fault on the junction of the North and South Bismarck Sea Plates, an extension to the northwest of the strike-slip Weitin Fault across Southern New Ireland. This earthquake was felt strongly in Rabaul and was recorded on a GA accelerograph at Rabaul Observatory, as shown in Figure 8.

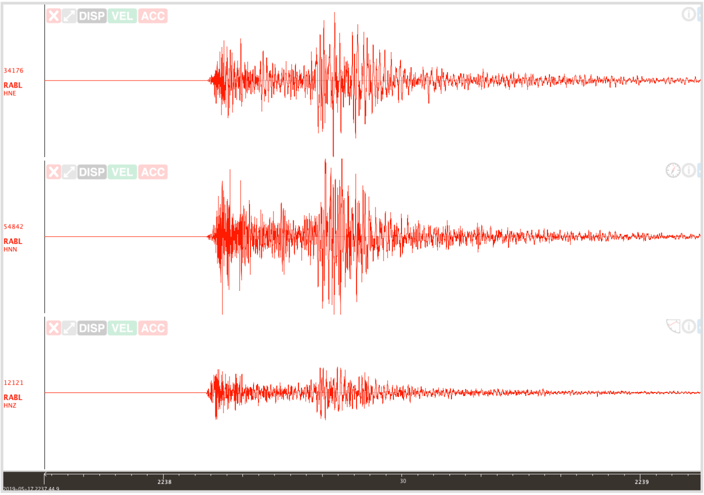
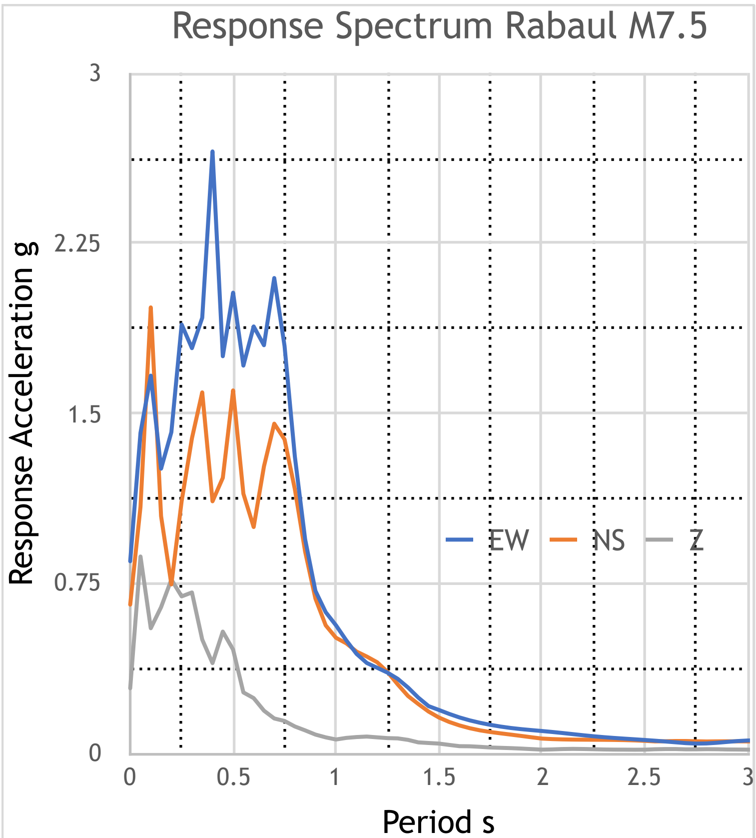


Figure 8 A record of the ground acceleration at Rabaul Observatory during the major M7.5 earthquake on 17 May 2019, east (top), north and vertical (bottom) components (Data from Geoscience Australia).

Few aftershocks were recorded, just one large M6.1 event also on the Weitin Fault at the southern end of the island. Response spectra for both earthquakes are shown in Figure 9.



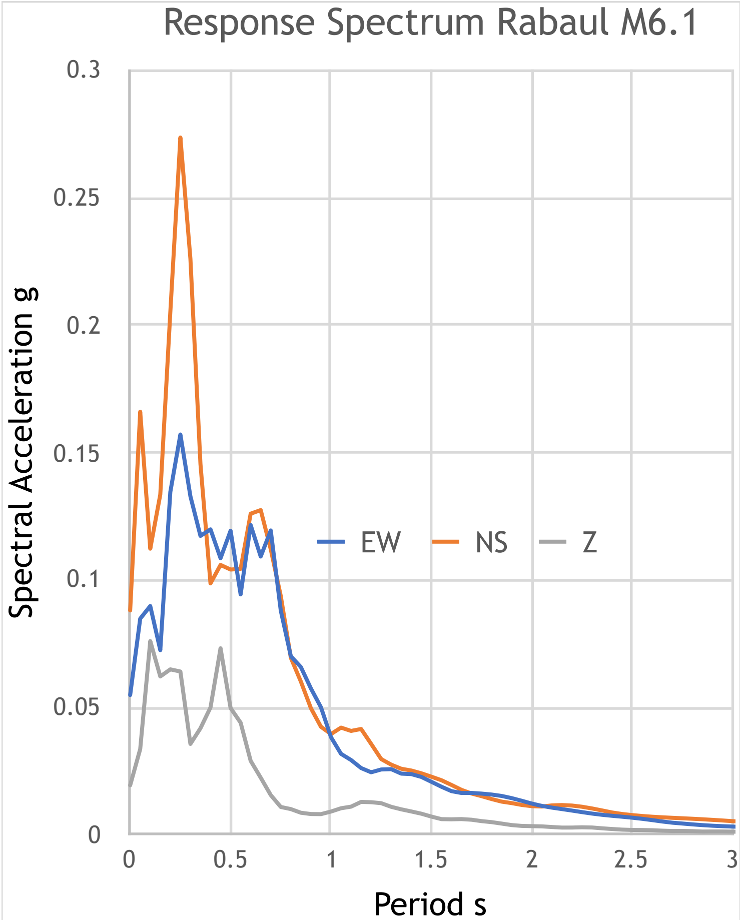


Figure 9 Response Spectra Rabaul, magnitude 7.5 earthquake (above) and M6.1 aftershock (below).

In November 2000, a magnitude 8 earthquake ruptured the Bismarck Sea lineament separating the North and South Bismarck Sea Plates, at its closest barely 30km northeast of Rabaul (Tregoning and others, 2001). A 6m surface fault rupture on the Weitin Fault across Southern New Ireland was mapped by Park and Mori (2007). The recorded strong motion at Rabaul Observatory has never been published. Rabaul Observatory is now host to a Geoscience Australia 6-channel recorder, the accelerometer a KMIFBA23 sampling at 200samples/s.

For interest we have plotted four spectra on one graph, the M7.5, M6.3, M6.1 and M5.8 earthquakes (Figure 10), all near Rabaul in East New Britain. The M8 earthquake on the Weitin Fault in 2000 would have nicely completed the graph. The figure shows the spectral acceleration increasing with magnitude. Also the corner period increases from 5.8 to 6.3 but then unexpectedly shows no change to the M7.5 recording in Rabaul.

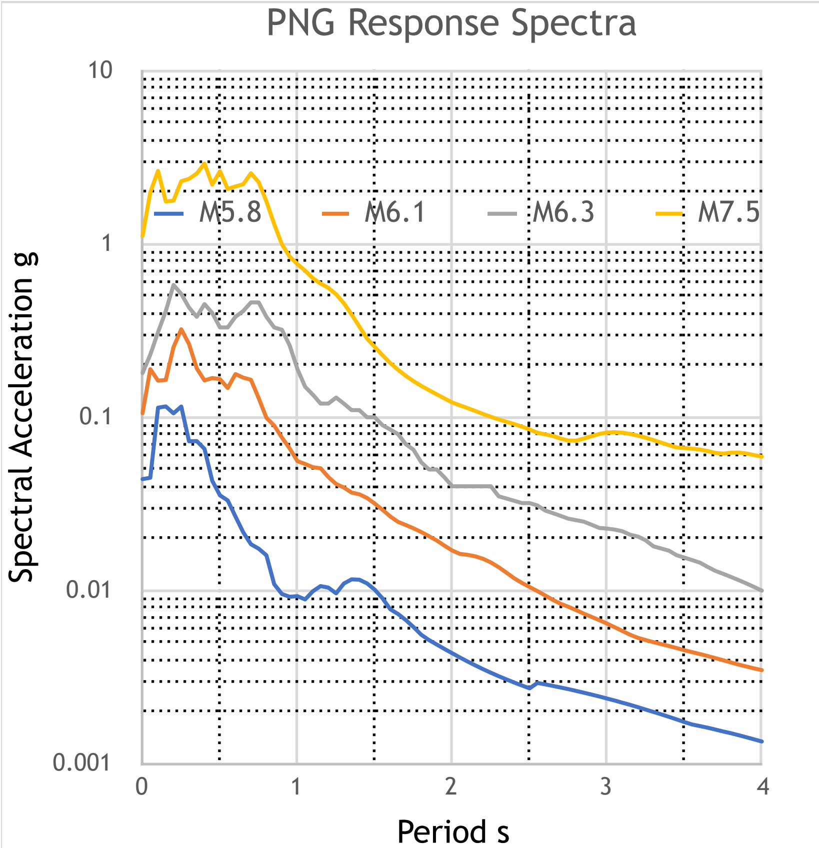


Figure 10 Comparison of response spectra in PNG over a range of magnitudes normalised for approximately 35km distance.

On 29 March 2015 at 23:48 UTC, a major Mw 7.5 shallow earthquake 75km southeast of Rabaul shook the town and was recorded on the accelerograph installed by Geoscience Australia at the Rabaul Volcano Observatory, the earthquake location at 4.73°S 152.56°E, depth 40 km. The mechanism is a shallow thrust, the principal stress direction north-south and perpendicular to the Solomon Sea Plate boundary to the south.

The Observatory is on a tuff ridge radiating from Kabiu "The Mother" volcano, the tuff overlying volcanics.The computed response spectra at Rabaul are compared with the 2015 recorded earthquake magnitude M7.5 and the simulated event (Figure 11) produced using Greens Functions by Sinadinovski and McCue (2015). Although at a slightly larger epicentral distance and greater depth, their analysis shows broad general agreement with the observed spectra; the vertical simulated response is less than observed, but the horizontal simulated response is surprisingly higher than observed at periods above 1s.

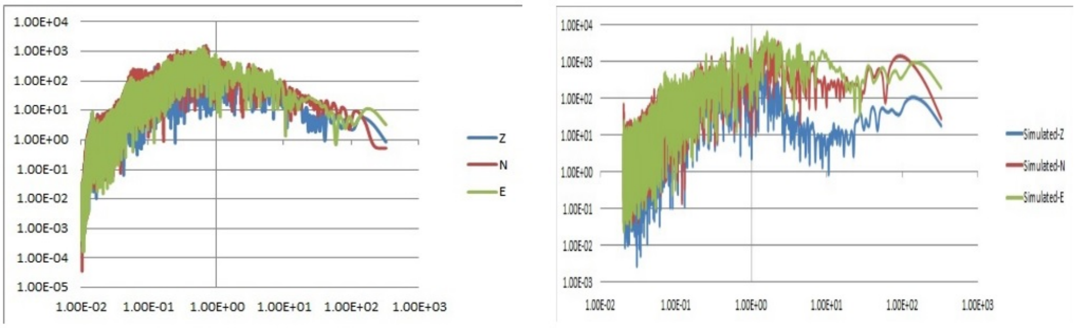


Figure 11. Amplitude Spectra of the 2015 accelerogram at Rabaul (left) and of the synthetic (right) for all three components, acceleration in cm/s2 versus frequency Hz.

PNG CODE SPECTRA

It is interesting to compare the spectra in Figure 10 with those proposed for the current Loading Code by Jury and others, 1982, their Figure 14, our Figure 12.

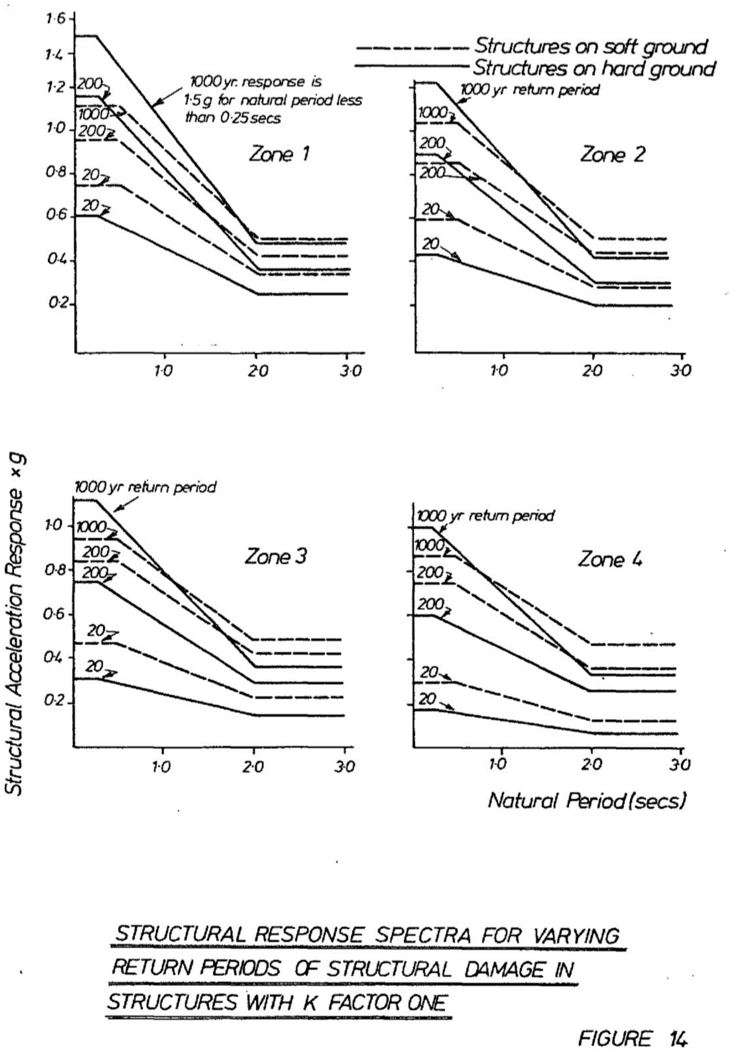


Figure 12 Spectra developed for the PNG Building Code, 1982

They zoned the hazard with 4 zones, 1 the highest, 4 the lowest and for firm ground and hard ground. Various return periods were considered, not 475years but it can be interpolated between 200 and 1000 years. The code spectra plateau amplitude at short periods for 1000 year return period is about half that recorded during the magnitude 7.5 earthquake at 35km closest distance (Figure 10), and the corner frequency is about 0.25s whereas the recorded ground shaking is flat to about 0.75s. The code design earthquake is quite un-conservative compared with that recorded.

DISCUSSION

The PNG strong motion monitoring program begun back in the late 1960s by Boyce, Denham, Everingham, Ripper, Gaull and later Letz and others, is finally providing results thanks to the change from analogue to digital recording.

In this study we analysed earthquake records in the Tari region (2018) of Hela Province and Rabaul (2019) and Warangoi (1978) in the East New Britain Province. The recent earthquakes were recorded digitally and continuously at 200s/s but at Warangoi, the ground shaking was recorded on a triggered analogue Kinemetrics SMA-1 recorder. We re-digitized the 70mm film at 100samples/s.

The magnitudes of the earthquakes were 5.8, 6.1, 6.3 and 7.5 with nearest source distances of 20 to 50km. The earthquake mechanisms were either thrust or strike-slip, all were shallow. Calculation were made over a wide frequency range typically 0.1 to 10 Hz (10s to 0.1s period).

The lack of a strong foundation signal in the 6 Hela Province accelerograms leads us to think that this parameter can be largely ignored in PNG where there are few examples of outcropping high shear modulus crystalline rock akin to many parts of Australia. The exception are sites subject to liquefaction or on reclaimed land where special earthquake design precautions are warranted for the foundations. We would call the Rabaul and Hela Province recording sites average foundations for PNG.

The majority of the spectral peaks are between 0.1 and 0.8 sec. The maximum spectral acceleration, at Rabaul during the 2019 M7.5 earthquake, is 2.7g and the width of the flat section of the spectra are magnitude dependent and may also be a function of the regional geology and source mechanism. However the spectral shapes of the 2018 Hela and 2019 ENBP province spectra have very similar shapes, and the plateau amplitudes in Figure 10 approximately scale with magnitude. We suppose that the 2018 mainshock at Hela Province was probably quite comparable to that at Rabaul in the 2019 mainshock and so the spectrum can be used to represent the ground shaking of a shallow magnitude 7.5 earthquake anywhere in PNG.

According to McCue (1982), between 1901 and 1978, the expected average return period for a magnitude 7.5 earthquake in the New Guinea region (130 - 165E) was between 2 and 3 years. Since then, according to the ISC, there have been 23 earthquake in the period 1979 to May 2017, in line with that expectation.

Locally recorded data are far superior to modelled data but until sufficient data are recorded we can't say whether the ground shaking varies significantly between shallow subduction and shallow thrust or even strike-slip earthquakes. The ground motion at Rabaul recorded on 17 May 2019, and its spectrum, are our recommended design ground motion for the active parts of Papua New Guinea in place of the 1982 Earthquake Code, for buildings and structures on average foundations. Active parts being the South coast of New Britain, west coast of Bougainville and north coast of New Guinea, for normal buildings and structures. It is also suitable for the less active parts of PNG; Papuan Peninsula and south coast of New Guinea, for special structures on average foundations, the importance factor trading off against the zone factor.

The spectrum could also be used throughout the seismically active areas of the Southwest Pacific such as Vanuatu until local data are acquired. More strong motion instruments are needed, especially in cities and at nationally important facilities such as dams, mines and oil fields.

It is open to discussion whether some of the PNG strong motion records from shallow earthquakes to magnitude 6.3 might be applicable in the Sydney Basin and Victoria for example, for Newcastle, Sydney, Melbourne and Geelong.

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