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Seismic Microzoning of the Ground Shaking Hazard from Soil Geotechnical Properties, Gisborne, New Zealand.

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SUMMARY

Gisborne is an urban area built upon young, soft, unconsolidated sediments. The extent of damage in the magnitude 6.3 Ormond earthquake near Gisborne in August 1993, and subsequent felt intensity surveys (MM V-VI) confirmed that the pattern of shaking and damage was not uniform. Geotechnical testing was undertaken to investigate the strength and deformation properties of the soils underlying Gisborne. Analysis and modelling of Earthquake Commission (EQC) claims from the Ormond earthquake were carried out to construct a claim density contour map. The map revealed two anomalous areas of high claim density in the northern suburbs of Mangapapa and Whataupoko compared to the rest of the city. Investigation of the underlying Neogene basement topography revealed the presence of sediment infilled valleys underneath or very close to each of the two claim density highs. The greater damage and anomalous claim density highs may have been caused by ground motion amplification at frequencies close to natural site periods, enhanced by resonance effects within the infilled sediment.

1. INTRODUCTION

Gisborne (45,780 people - 1996 census), is located on the eastern coast of the North Island of New Zealand (Figure 1). The region is part of a seismically active zone where the oceanic lithosphere of the Pacific Plate is being subducted beneath continental crust of the Australian Plate. In an average year around 13 earthquakes of magnitude 4.0 or larger, and less than 60 km in depth, occur within 100 km of Gisborne (Hamilton 1969).

The city of Gisborne overlies young, soft unconsolidated sediments of Holocene age, built up of alluvial and coastal deposits by successive flooding and fluctuating sea level. The topography of the underlying Neogene basement siltstones and mudstones is variable and buried by up to 40 m of sediment. Studies by Borcherdt (1985) and Hough et. al. (1990) have shown that the sediment through which seismic waves pass can affect the velocity and amplitude of the waves, particularly for areas of young unconsolidated sediments such as those underlying Gisborne.

The extent of damage in the magnitude 6.3 10 August 1993 Ormond earthquake to the city of Gisborne and subsequent felt intensity surveys (MM V-VI) have confirmed that the pattern of damage and shaking was not uniform. It was evident that shaking was much greater in the northern suburbs of Mangapapa and Whataupoko.

2. EARTHQUAKES IN THE GISBORNE REGION

2.1 Return Periods

Earthquake hazard is usually evaluated in terms of Return Period, which is the average time between occurrences for a shock of some particular magnitude or intensity. Table 1 summarises mean return periods for various Modified Mercalli (MM) intensities for the Gisborne Region.

The actual felt intensity is dependent upon the magnitude and characteristics of the source event, distance from source, and the materials through which the waves travel. The calculated return periods take into account the effect of the regional geology or average ground conditions, but do not account for local site conditions. Unfavourable site conditions such as young alluvial deposits can cause an increase in the intensity by 1 or 2 units on the Modified Mercalli (MM) scale and a decrease in return periods (Smith 1990).

MM Intensity	Return Period (Years)
> VI	10
> VII	50
> VIII	200
> IX	1000

Table 1: Mean Return Periods for Earthquakes in the Gisborne Region (adapted from Smith and Berryman 1986)

Felt intensities as high as MM VII have occurred in Gisborne this century. These intensities were felt in the 1931 magnitude 7.9 Napier earthquake, the 1932 magnitude 6.8 Wairoa earthquake, the 1966 magnitude 6.2 Gisborne Earthquake and the magnitude 6.3 1993 Ormond earthquake. Other notable earthquakes which have caused MM intensities of VI occurred in 1914, 1931, 1947 and 1960.

2.2 1993 Ormond Earthquake

The Ormond earthquake epicentre occurred 25 km northwest of Gisborne at approximately 2150 hours on August 10 1993. The event was a magnitude M_L 6.3 event with its focal depth at 48 km and its epicentre located at 38.52°S 177.93°E between Ormond and Waimata (Figure 1). A swarm of aftershocks occurred some 10 km further west of the earthquake epicentre at a focal depth of 36 km (Read and Cousins 1994).

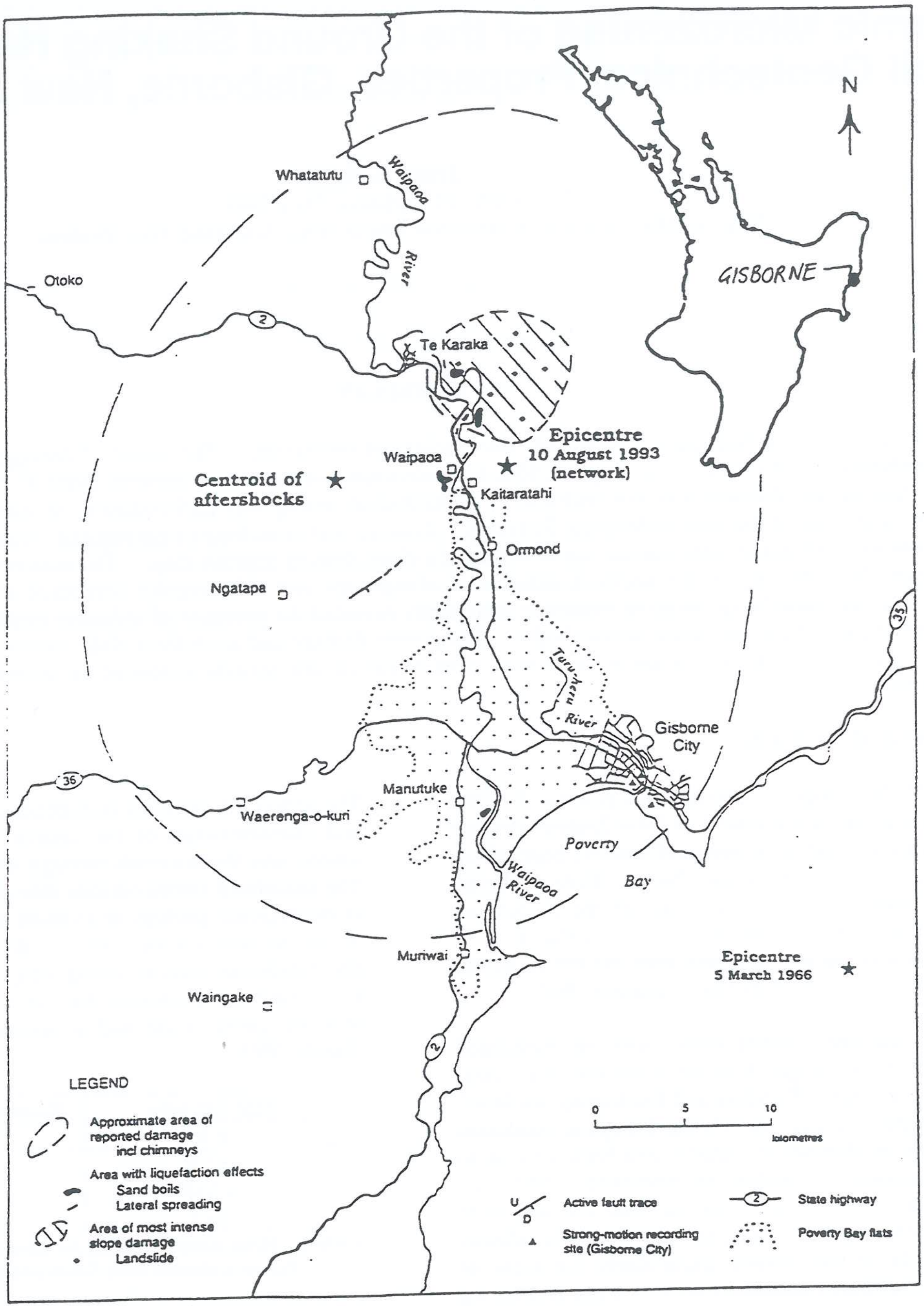

Figure 1: Location Map and Map of Ground Damage Features for the August 1993 Ormond Earthquake

There were reports of strong to moderate shaking over more than 1000 km^2 in the Gisborne region and lesser shaking in Tolaga Bay, Wairoa and Napier (Read and Cousins 1994). Newspaper and Seismological Observatory surveys reported MM intensities of VII, felt in an area of approximately 600 km^2 (Figure 1) and were centred around the epicentre of the aftershocks (Read and Cousins 1994). Maximum peak ground accelerations of 0.24g were recorded in Gisborne City.

2.3 Damage to Gisborne City

Within the city itself, intensities ranging between MM V and MM VI were recorded with the differing intensities felt throughout the city suggesting some variability in ground motion. Higher intensities of MM VI were more prevalent north of the city centre in the suburbs of Whataupoko and Mangapapa, with minor pockets of MM VII (Read and Cousins 1994). Wells (1994) also reported definite microzoning effects around Perry St in the suburb of Mangapapa. Lesser intensities of MM V were more common southwest of the Taruheru River and northeast of the city centre in the suburb of Kaiti.

Strong motion data recorded in Gisborne was higher than expected for MM V-VI intensity shaking based on the attenuation relationship developed by Dowrick (1992). However, shaking in the Ormond earthquake was generally less severe in Gisborne than that produced by the shallower 1966 M_L 6.2 earthquake which produced MM intensities of VI-VII and peak ground accelerations of 0.28g.

3. GEOTECHNICAL INVESTIGATION

3.1 Geotechnical Testing

The geotechnical properties of Gisborne soils were investigated by Cone Penetrometer Testing at 19 sites in May 1995. The locations are shown in Figure 2. In addition, 24 shallow test pits were excavated at selected sites across the city to determine soil properties in the upper metre of the soil profile and provide samples for laboratory testing. At each CPT site the soil profile was characterised by soil types assigned using Robertson and Campanella (1983).

Shear modulus (G), Young's modulus (E) and Poisson's ratio (v) were then determined for each soil layer from empirical relationships between cone resistance, void ratio and overburden pressure using methods given in Lambe and Whitman (1979) and Mayne and Rix (1993). Further parameters such as shear-wave velocity (V_S) and seismic impedance ratio (a measure of seismic rigidity) were also calculated from relationships with strength modulus, shear wave velocity and bulk density.

For each CPT site a depth weighted mean value was determined for each of the above geotechnical parameters using a method adapted from Fumal and Tinsley (1985) to establish shear-wave velocities for the Los Angeles Region. To determine the depth weighted mean, the thickness of each layer was divided by the mean geotechnical parameter assigned to that layer. This figure was then totalled down the profile and then divided by the total depth of the profile.

Testing of the underlying soils in Gisborne shows they have variable properties both vertically down the profile, and laterally throughout the city. The suburbs of Te Hapara and Elgin are underlain by varying thicknesses of sands, silty sands and sand mixtures, which in turn overlie clays. The sands are generally of loose to medium density, while the clays range from soft to firm in consistency. Gisborne Central is also underlain by these loose to medium dense sands and sand mixtures.

Sands form the upper part of the profile in Mangapapa but thin out towards the east and north, where clays form most of the profile. The density of the sands ranged from loose to medium dense. The clays are generally soft, but are interbedded with stiff clays and silty clays. Soft to very soft clays are dominant in Whataupoko. Some sands overlie and cap these clays in the southern part of the suburb. The soil profile of Kaiti is also dominated by clays, however, the consistency of the clay varies from soft to very stiff. The soft clays generally form the lower part of the profile. Stiff silty clays and silt mixtures are interbedded within the soft clays.

The strength and deformation properties were generally greater for the suburbs of Elgin, Te Hapara and Kaiti, while the soils of Mangapapa and Whataupoko, and the northern part of Gisborne Central were generally weaker. These geotechnical properties are summarised in Table 2.

3.2 Investigation of the Neogene Basement Topography

The subsurface Neogene basement (mudstone) topography was delineated and mapped (Figure 2) with data from a number of sources, including cone penetrometer testing and borelogs from geotechnical investigations around the city. The basement rock also outcrops in several locations in Mangapapa and Whataupoko, as well as around the mouth of the Turanganui River, while basement depths from CPT testing were assumed where cone refusal occurred (q_c>30 MPa).

Depth to basement appears to be greatest beneath Gisborne Central (around 40 metres), with basement depths decreasing towards the hills in Mangapapa, Whataupoko and Kaiti, and increasing out into the Gisborne Plains.

Figure 2 shows there is some variability in the underlying topography of the basement beneath Gisborne. Reports of MM VI and VII in the 1993 Ormond earthquake appear to coincide with sediment thickness of 6 to 10 metres in the suburbs of Whataupoko and Mangapapa. This contour is thought to be the edge of the buried wave-cut platform composed of harder mudstone, buried by softer mud and overlain with sand (Lensen 1969). The position of the 8 and 10 metre contours through these suburbs also approximately coincides with the shearing of service pipes in the 1966 earthquake. Figure 2 also shows reasonable correlation with a map of sediment thickness/depth to basement from a seismic noise study carried out by Hatherton and Orr (1971).

4. GROUND SHAKING HAZARD

Regional ground shaking can be estimated by intensities deduced from calculated return periods, but these statistical values only account for the effects on regional geology and average site conditions. They do not account for unfavourable site conditions which can cause an increase in the intensity by one or two units on the Modified Mercalli scale and a decrease in return periods (Smith 1990). It seems reasonable that this variation in ground shaking might be a consequence of the thickness of the unconsolidated material and the characteristics of the materials themselves.

Suburb	Normalised Cone Resistance q_{c1} MPa	Youngs Modulus E MPa	Shear Modulus G MPa	Shear Wave Velocity V_S m/s	Seismic Impedance Ratio
Te Hapara, Elgin Gisborne Central	1.6-8.6	142-290	47-97	162-225	4.1-7.4
Mangapapa	1.0-4.3	118-211	40-70	149-195	4.8-7.0
Whataupoko	0.9-1.3	87-115	29-38	133-151	7.4-8.6
Kaiti	1.4-3.1	100-201	33-67	141-194	5.7-7.5

Table 2: Summary of strength & deformation properties

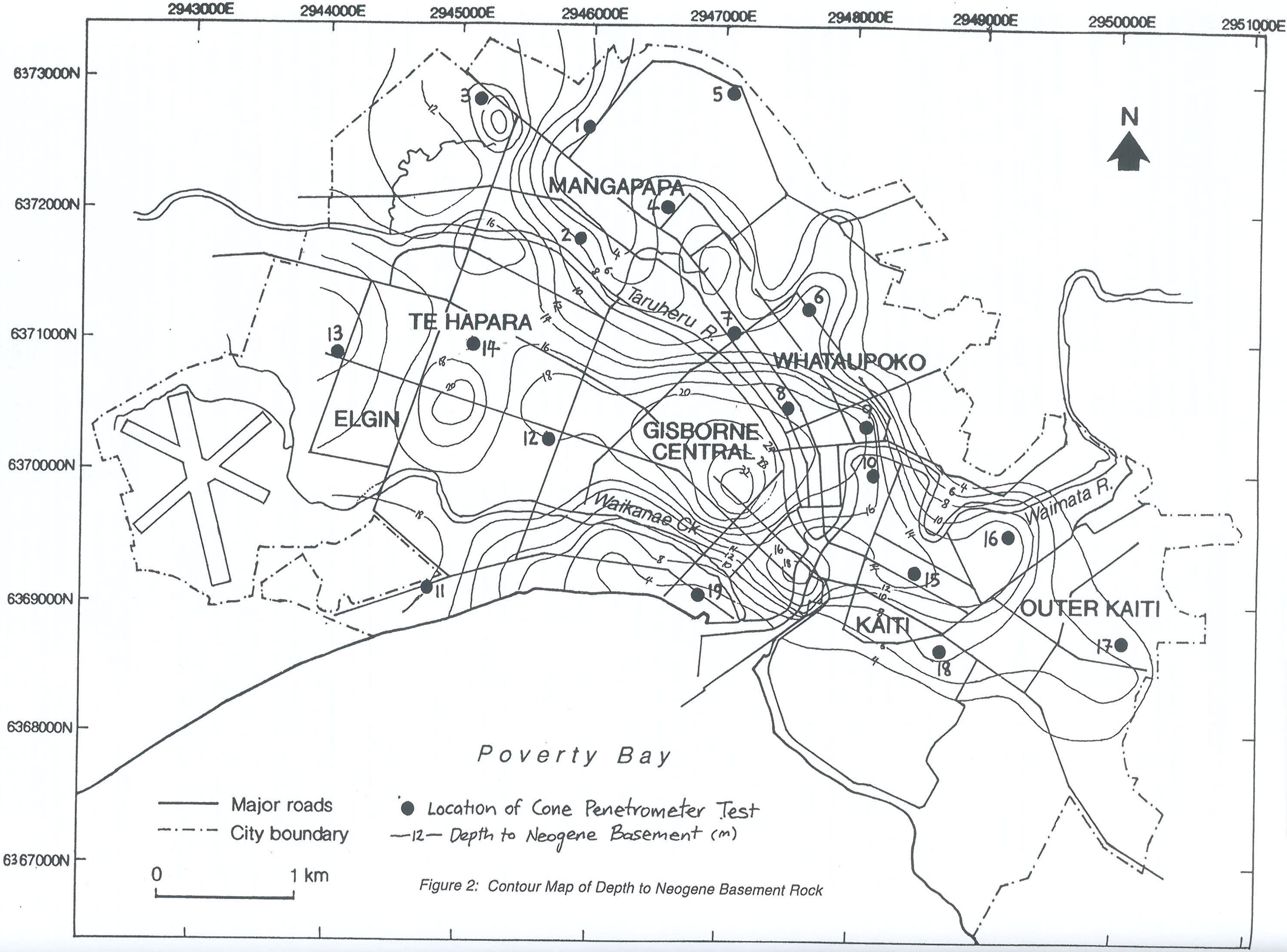

Figure 2: Contour Map of Depth to Neogene Basement Rock

Thus, the composition of near surface materials is also as important as the distance from the earthquake epicentre. Studies (e.g. Rogers et al. 1979, Geli et al. 1988) have also shown that the topography or structure of the basement rock underlying these unconsolidated sediments can also affect the degree of shaking, also causing amplitude enhancement of the seismic waves. The study of these effects and their geographic variation are useful for earthquake microzoning purposes.

4.1 EQC Claim Damage from the 1993 Earthquake

Following the 1993 Ormond earthquake, surveys to assess the degree of shaking intensity and damage to the Gisborne region were undertaken by Civil Defence and IGNS. In addition, the results of the Earthquake Commission (EQC) claims were modelled to assess which areas of Gisborne were more damaged than other areas by the effects of increased ground motion

Around 2800 claims were made to the EQC for damage totalling $4 million, with 797 claims for the city of Gisborne. Claim densities and damage parameters were then calculated from the EQC data set. Claim density (CDen) was calculated as claims per square kilometre (claims/km^2) while a damage factor (DF) was calculated as the ratio of EQC claims per thousand dwellings. Claim density and damage factor are given by:

[1] $$CDen = \frac{n}{area} \qquad \textit{where } n = \textit{number of claims}$$

[2] $$DF = \frac{n}{1000\ dwellings}$$

EQC claim densities and damage factors given in Table 3 clearly show the suburbs of Mangapapa and especially Whataupoko as having greater claim densities per area and per 1000 dwellings than any other suburbs. The claim density for Whataupoko was around 50% greater than other suburbs to the south and east.

To determine which areas of Gisborne experienced the greatest damage, a contour map of EQC claim density was constructed (Figure 3). In the absence of detailed MM intensity data, contouring EQC claim densities allowed determination of areas of high or anomalous claim density, and thus, delineation of areas of greater ground shaking. Claim densities from the EQC data set in Figure 3 are presented as number of claims per two hundred square metres (claims/200m^2), with the smaller area allowing the pattern of damage to be studied more closely.

The contour map shows two definite anomalous claim density highs of up to 36 claims/200m^2 in Mangapapa and Whataupoko - one around Walsh St in Mangapapa and the other near Whitaker St in Whataupoko. Walsh St is approximately 200 metres from Perry St, reported by Wells (1994) as an area of definite microzoning effects in the 1993 earthquake. Structures in these suburbs are predominantly light timber frame residential dwellings of one or two stories. Claim densities over the rest of Gisborne ranged from six to twelve claims/200m^2. In addition, a smaller peak of around 22 claims/200m^2, occurred in Mangapapa near the intersection of Valley Rd and Gordon St.

4.2 Relationship between Geotechnical Properties and Damage

To test if there are relationships between the damage pattern and geotechnical properties, the data was analysed using simple linear regression and fitting a straight line through the data using the least squares method. An arbitrary value of $r \geq 0.7$ ($r^2 \geq 0.5$) was used to delineate between significant and insignificant correlations. The geotechnical properties (depth weighted mean values from CPT testing) have been used as the independent variable and the claim density (claims/200m^2) at each test site as the dependent variable. Claim density values were derived from the EQC data contoured in Figure 3. Results of the analysis are given in Table 4.

In general, the geotechnical properties of Gisbornes soils determined by cone penetrometer testing, relate well with claim density. Claim densities were lower on soils with greater (stronger) geotechnical properties or lower impedance ratio. Thus, the stronger the soil the less damage that would be expected in an earthquake due to ground shaking. However, this analysis did not explain the anomalous claim density highs, nor their locations.

4.3 Shear-Wave Velocity and Impedance Differences

Studies in the Los Angeles region have indicated that shear-wave velocity is a critical factor in determining the amplitude of ground motion (Fumal and Tinsley 1985). Shear-wave velocity is also an important element in parameters such as the seismic impedance ratio and attenuation.

Good correlations with claim density, allows shear-wave velocity to be used as a means of approximating the response of a deposit to seismic shaking. Shear-wave velocity is also a useful index of the stiffness (an indicator of strength), relative density and consistency of a sediment (Tinsley and Fumal 1985). Studies have also found an inverse relationship between average shear-wave velocities and MM intensities (Borcherdt et al. 1979). Bevin (1995) constructed a contour map of mean shear-wave velocities for Gisborne which showed good correlations with reported MM intensities in the 1993 Ormond earthquake, and with the EQC claim densities in Figure 3. Shear-wave velocities were generally lower in Whataupoko and Mangapapa than the other suburbs. Lower claim densities (<10 claims/200m^2) were also located in areas of higher shear-wave velocity (e.g. Elgin, Te Hapara and Kaiti).

Previous studies have also shown shaking response is greatest where impedance contrasts between surficial and subjacent layers is greatest (Tinsley and Fumal 1985). Thus, at sites of large impedance differences, as the seismic waves propagate upwards, they pass into layers of lower impedance. The resistance to particle motion decreases and the amplitude of the seismic wave increases (Reiter 1990), resulting in greater shaking. Therefore, areas of weaker material overlying stronger material such as very stiff clays or basement rock would expect greater shaking. The largest impedance ratios (7.4 to 8.6) generally occurred in the suburb of Whataupoko, where MM intensities of at least VI were felt.

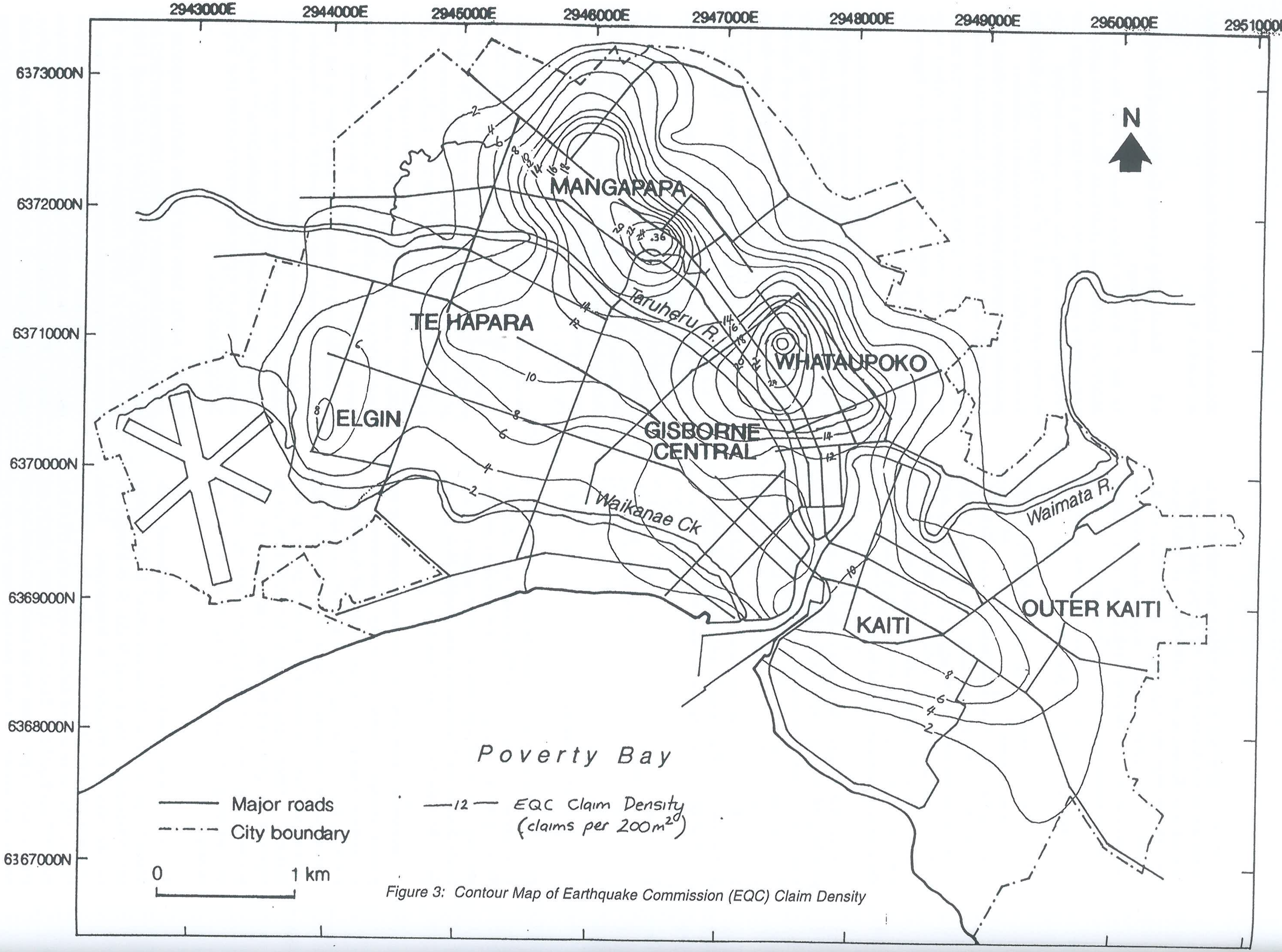

Figure 3: Contour Map of Earthquake Commission (EQC) Claim Density

	Mangapapa	Whataupoko	Kaiti	Gisborne Central	Te Hapara	Elgin
No. Claims (Cl)	220	200	143	107	81	46
% Claims of Total	27.6	25.1	7.9	13.4	10.2	5.8
Total Cost ($)	$556,318	$481,432	$332,307	$307,629	$153,599	$76,320
Mean Cost ($)	$2,564	$2,350	$2,324	$2,902	$1,896	$1,659
Population (1991)	5436	3477	7509	3393	4212	2838
Approx. Area (km^2)	5.78	3.39	6.36	4.02	3.26	3.50
Claim Density Cl/km^2)	38.1	59.0	22.5	26.2	24.8	13.1
Damage Factor Cl/1000 dwellings)	122	153	61	86	52	49

Table 3: Summary and Breakdown of EQC Claims by Suburb for the 1993 Ormond Earthquake

4.4 Resonance, Site Amplification, Response Spectra and Damage

The greatest damage occurred in the Suburbs of Mangapapa and Whataupoko, where the sediment thickness (depth to basement) is 6-16 m (Figure 2). Overlaying Figures 2 and 3 shows that the location of the two anomalous claim density highs appear to overlie sediment infilled Neogene valleys with depths to basement in the base of these valleys also ranging from 6 to 12 metres. The location of these highs also approximately corresponds to the edge of the wave-cut platform shown in Hamilton (1969).

Seismic waves entering these sediment infilled valleys may become trapped and begin to reverberate, giving rise to resonance effects, with the configuration of the underlying topography affecting the amplitude of the seismic waves. A sediment layer is expected to give rise to resonance with frequency given by the relationship:

$$[3] \quad f_1 = \frac{V_s}{4H}$$

where V_S is the shear-wave velocity, H is the layer thickness and f_1 is the resonant frequency (Hz) of the fundamental mode (Hough et al. 1990). The Neogene valleys have shear-wave velocities of approximately 130m/s (mean of CPT sites 6, 7 and 8) and sediment thickness ranging between 6 and 12 metres. From Equation 3, a sediment thickness of 12 metres would imply a resonant frequency (fundamental site period) of 2.7 H_Z (T = 0.37s). Response is at its maximum when the reverberating waves are in phase which each other and is a frequency-dependent phenomena.

Response spectra from the 1993 Ormond earthquake is available for three sites in Gisborne (Read and Cousins 1994). Two of these sites, the CPO and 2ZG sites (in central Gisborne), are soft soil sites with basement depths of up to 35 to 40m. Maximum amplification of peak surface motions here occurred at periods of 0.35 and 0.40s (2.86 and 2.50H_Z). The natural period of these two sites (given by equation 3) is 1.0 to 1.1s respectively (Zhao et al. 1995), so site amplification from resonance effects is unlikely as the natural period of the site and the period at which peak surface motions occurred do not match. However, for the sediment infilled valleys these peak surface motions of 0.35 to 0.40s are very close to natural site periods, so the greater damage and anomalous claim density highs may have been caused by ground motion amplification at these frequencies. These site amplification effects are considered to be one of the major causes of damage to buildings as a result of earthquakes (Hough et al. 1990), especially in the short period band of 0.3-0.5s (2.0-3.3 Hz). Ground motion characterised by these fundamental periods is of greatest significance to buildings of less than four stories (Rogers et al. 1985), the case for much of Gisborne.

Sediment in the Neogene valleys gives rise to resonant frequencies in phase with one quarter of the expected wavelength. Thus, seismic waves entering these Neogene valleys will reverberate causing amplification of ground motion because the fundamental site period (and frequency) is in the vulnerable range. Response spectra for sites of thicker sediment in Gisborne (CPO and 2ZG sites) have peaks close to that required for resonance behaviour in the Neogene valleys. Marks and Larkin (1995) have also demonstrated amplification of peak ground motion at periods of T =0.4 to 0.5s for modelled infilled valleys similar to the Neogene valleys in Gisborne. Thus, it seems reasonable that this could be applicable for the infilled Neogene valleys and the anomalous claim densities underlying Mangapapa and Whataupoko.

Further study is required to confirm this hypothesis. Detailed seismic cone penetrometer testing would confirm shear-wave velocities through the sediment infilled valleys and delineate the underlying Neogene topography. A seismograph network could also be located in this area, on sites overlying the Neogene valleys, sites overlying the wave-cut platform and sites where the Neogene basement outcrops at the surface. Recordings of response spectra in smaller, more frequent earthquakes would help to confirm calculated wave amplitudes and site periods.

5 CONCLUSIONS

Geotechnical testing of the soils underlying Gisborne has shown they have variable properties both vertically down the profile, and laterally throughout the city. The geotechnical properties reflecting strength and deformation (moduli) were greatest for the suburbs of Elgin, Te Hapara and Kaiti while the soils of Mangapapa and Whataupoko, and the northern part of Gisborne Central are generally weaker.

Analysis and modelling of EQC claim damage from the 1993 Ormond earthquake has allowed determination of claim densities and the construction of a claim density contour map. Claim densities reveal two anomalous areas of very high claim density compared to the rest of the city. Claim densities were much greater in Mangapapa and Whataupoko, which correlated well with MM intensities from the earthquake. Construction of the claim density contour map allowed the location of these anomalous claim density highs to be determined, and to investigate the cause of these anomalies. Analysis of geotechnical testing by CPT and claim density showed good correlation, but did not completely explain the location of the anomalies.

Investigation of the underlying Neogene basement topography has shown the presence of sediment infilled valleys. Resonance effects are a strong argument for these high claim densities. The two anomalies plot very close to two Neogene valleys, which are infilled by 6 to 12 metres of sediment. Seismic waves with frequencies close to the natural site period could have caused site amplification effects, leading to greater shaking and felt intensity in the 1993 earthquake. This hypothesis is supported by research on site response of sediment infilled alluvial basins. Amplification of up to 0.8g can occur at periods of 0.4 to 0.5s. This is very close to natural site periods for the areas of the anomalous claim density.

Recent major earthquakes such as the Northridge earthquake (California 1994), Kobe (Japan 1995) and Taiwan (1999) are constant reminders of the destruction and loss of life earthquakes can cause, even in developed countries with strict building codes, disaster preparedness and earthquake response planning. So defining earthquake hazards in towns and cities, is an important planning tool.

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Linear Regression Parameter	Youngs Modulus E MPa	Shear Modulus G MPa	Shear Wave Velocity , Vs m/s	Seismic Impedance Ratio
n	19	19	19	19
M	-0.08	-0.24	-0.18	2.97
B	21.8	21.9	39.6	-7.9
r	0.75	0.76	0.75	0.70

where n is the number of data points; M, B are the slope and the intercept respectively for the regression CDen = M * X + B, where X is the geotechnical property, for which the correlation coefficient is r.

Table 4: Regression Analysis of Claim Damage and geotechnical properties at each CPT site.

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