Assessment of Strong Motion During 1989 Newcastle Earthquake

D.J. WILLIAMS
B.E., Ph.D., M.I.E.Aust.
Senior Lecturer in Civil Engineering, The University of Queensland

SUMMARY The strong motion data collected during recent earthquakes, particularly those occurring in seismically active regions of the world, has highlighted the importance of site conditions in determining amplification and the greater hazard posed by continental earthquakes compared with plate margin earthquakes of the same magnitude. The paper outlines an approach for assessing the strong motion during the 1989 Newcastle, Australia continental earthquake, for which only intensity data were available. It is shown that a rational and useful assessment is possible. From this assessment, estimates are made of the likely level of amplification which occurred during the Newcastle event, giving rise to the widespread damage observed. The estimated amplifications are shown to be in line with available worldwide data.

1. INTRODUCTION

The state-of-the-art of earthquake engineering has made rapid advances over the last few years, due largely to the strong motion data which has been collected during recent earthquakes in seismically active regions of the world. Acceleration data collected during the 1985 Michoachan earthquake, which caused considerable devastation to parts of Mexico City, demonstrated the extent to which soft soil deposits and structures of certain critical aspect ratios can amplify rock motions, particularly those of low amplitude and low frequency. While the possibility of amplification was known before this event (1,2), the level of amplification measured at Mexico City was far higher than anticipated. The 1989 Loma Prieta earthquake and subsequent aftershocks triggered numerous accelerometers in the surrounding area, providing the most valuable strong motion database in existence.

There is increasing appreciation of the importance of frequency and of the greater damage potential of a continental earthquake compared with one of similar magnitude occurring at a plate margin. However, there is a difficulty in assessing ground motions during the relatively infrequent and widely scattered earthquakes which occur in regions of relatively low earthquake hazard, due to the absence of strong motion instruments. Reliance must be placed on far-field seismograph records and macroseismic data in the form of "felt reports", from which intensities are assigned. In this paper, an assessment is made of the ground motions experienced during the damaging 1989 Newcastle, Australia continental earthquake, drawing on the data available for this event and making use of worldwide data to provide some validation of the results obtained. From this assessment, estimates are made of the likely level of amplification which occurred during the Newcastle event, giving rise to the widespread damage observed. The estimated amplifications are shown to be in line with available worldwide data.

2. SITE SPECIFIC AMPLIFICATION

Okamoto (1) suggested that the considerable differences in the levels of earthquake damage sustained at sites roughly equi-distant from the epicentre of a given earthquake are due mainly to differences in ground conditions. The amplification of ground shaking and resulting greater damage which can occur at soft soil sites was explained in terms of the resonance of the soil column due to multiple reflections of the incident waves. Resonance is a function of the thickness, density, and shear wave velocity of the soil profile, the density and shear wave velocity of the bedrock, and the amplitude and frequency content of the earthquake ground motions. The soil profile is generally non-homogeneous and multi-layered, and the properties of the bedrock may also vary. Okamoto presented measured data indicating amplification up through a weathered rock profile in excess of 2-fold, and similar amplifications up through a soft soil profile. Reclaimed land overlying soft soils was identified as being particularly susceptible to amplification and earthquake damage.

The degree of amplification across a material boundary is a function of the impedance gradient across the boundary, impedance being the square root of the product of the material density and its shear wave velocity. Simplified analyses (1) involving a single homogeneous, elastic soil layer overlying homogeneous, elastic bedrock suggested amplifications of up to 10-fold. Up to a 2-fold amplification was predicted across the rock/soil interface, although the greater the impedance gradient from hard to soft material, the more difficult it is for the earthquake energy to be transmitted. The reflection of ground motion at the ground surface can lead to a further doubling of the incident ground motion. Resonance accounted for the remainder of the amplification. In the more general case of a non-homogeneous, multi-layered subsurface conditions, complex ground motions will result from the transmission and relection of ground motions at material boundaries. The most marked amplification will occur close to the ground surface, particularly if, as is likely, the softest layer exists at the surface. The effects of reflection, refraction and scattering of ground motions across a material interface can reduce the amplitude of the ground motions significantly (a 35 % reduction is suggested in 3). Non-elastic material behaviour may result in only about half the amplification predicted for elastic material behaviour.

Joyner and Boore (4) suggested that resonance of the soil column does not usually dominate amplification since ground shaking covers a range of frequencies apart from the resonant one. They suggested that amplification is more usually dominated by the low shear wave velocity or, more precisely, low impedance of the layers towards the ground surface. For strong ground motion frequencies of greater than 3 Hz, attenuation in soils appears to dominate over amplification.

Finn (5) noted that at low levels of earthquake shaking the ground response will be essentially elastic. With increasing shaking level, the elastic shear modulus of the ground G, which controls the instantaneous response, will soften raising the site period and the damping, thus changing the response. While the response of Mexico City's lakebed deposits to the distant (hence low level input ground motions) 1985 Michoacan earthquake was largely elastic, the response of the San Francisco Bay region to the 1989 Loma Prieta earthquake was decidedly non-elastic. In the former case, the input ground motions were amplified 3 to 5-fold, producing peak ground surface accelerations approaching 0.2 g (where g is the gravitational constant equal to 9.81 $m.s^{-2}$). The response of the lakebed clays remained essentially elastic because the shear modulus of these high plasticity clays did not show substantial degradation until a shear strain level of about 0.1 %, and hysteretic damping was also low. This allowed greater amplification close to the ground surface than would have occurred if non-elastic effects had been substantial. At Treasure Island, in the San Francisco Bay region, the observed amplification during the Loma Prieta mainshock was 2 to 3-fold, limited by the non-elastic response of the soft bay mud and surface fill. Amplification at the same site during the smaller amplitude aftershocks was much greater, since the ground response to these was essentially elastic.

Based on limited data, Seed and Idriss (2) proposed approximate relationships between peak accelerations on rock and those on other ground conditions, indicating attenuation of rock accelerations greater than 0.1 g through soils, and amplification of rock accelerations less than 0.1 g. Based on acceleration data collected at soft soil sites during the Michoacan and Loma Prieta earthquakes, and on the results of analyses, Idriss (6) proposed for empirical correlation a median relationship between peak accelerations on rock and those on soft soil sites indicating amplification through overlying soft soils of rock motions up to 0.4 g.

3. CONTINENTAL VERSUS PLATE MARGIN EARTHQUAKES

Seed and Idriss (2) showed that attenuation relationships for continental eastern United States earthquakes indicated lower peak horizontal ground accelerations in the near-field, but a slower rate of decay and consequently higher accelerations in the far-field, compared with those for plate margin western United States earthquakes. Whitman and Algermissen (7) reported that peak ground accelerations measured during recent eastern Canadian (continental) earthquakes were much larger, for comparable magnitude and epicentral distance, than those recorded during Californian (plate margin) earthquakes, and had much higher predominant periods. The midwestern region of the United States shows relatively slow attenuation of intensity, which is thought to be due to the hard, intact nature of the bedrock, and the considerable depth of poorly consolidated materials overlying the rock, particularly in the Mississippi floodplain.

Jacob (8) noted that the rock shear wave velocity adopted as a reference in the United States Uniform Building Code (UBC) is 800 $m.s^{-1}$. While this may be appropriate for Californian bedrock, the eastern United States bedrock typically has a shear wave velocity about 4 times this value. Since amplification is proportional to the square root of the shear wave velocity contrast across a material boundary, for a given soil shear wave velocity, the higher rock shear wave velocity for the eastern United States compared with California should lead to about twice the amplification.

For the same size earthquake, continental earthquakes produce much larger damage and felt areas than plate margin earthquakes. Algermesson (9) observed that the 1811 Ms 8.3 New Madrid (continental) earthquake had a damage area of about 5000000 km^2, compared with about 180000 km^2 for the 1906 Ms 8.3 San Francisco (plate margin) earthquake. The 1989 Richter local magnitude M_L 5.6 Newcastle (continental) earthquake had a damage area of about 9000 km^2 and caused damage estimated at US$4 billion, compared with about 50 km^2 causing damage estimated at US$10 million for the 1989 M_L 5.5 Upland, Los Angeles (plate margin) earthquake (10). The corresponding felt areas were about 200000 km^2 and about 9000 km^2, respectively.

4. BRIEF DESCRIPTION OF 1989 NEWCASTLE EARTHQUAKE

4.1 Seismology

Rynn (11) presented a detailed assessment of the seismology of the 1989 Newcastle earthquake, which is briefly summarised herein. The earthquake occurred on 28 December 1989. It was of M_L 5.6, caused 13 fatalities, 160 injuries, and A$4 billion damage, including an insured loss of about A$1.2 billion, making it the most costly single natural disaster in Australian history. The damage area covered about 9000 km^2, and the felt area about 200000 km^2, with isolated felt reports up to 800 km from the epicentre. The epicentre was approximately located near Boolaroo, about 15 km west south west of the Newcastle Central Business District, based on far-field seismograph records. The epicentral location is only accurate to ± 15 km. The focus was approximately located at a depth of 11.5 km, based on data picked up at a seismograph station in Scotland. It could be more shallow. The focal mechanism was interpreted as a thrust mechanism with near horizontal principle stress direction, but no evidence of faulting or tectonic movement could be found at the ground surface. Significant recorded aftershocks were of M_L 2.7 on 29 December 1989, located 9 km west south west of the Newcastle Central Business District at a focal depth of 13.6 km, and M_L 2.5 on 27 February 1990 also near Boolaroo. No additional damage was reported after either event. Previous earthquakes of similar size to the mainshock occurred in the same area in 1868 and 1925.

Little strong motion data are available due to the lack of accelerometers in the region. The duration of shaking can only be guessed from personal observations, which put it in the range from 5 to 42 s. From instruments at coal mines in the region, 30 to 90 km from the epicentre, peak rock accelerations in the range 0.02g to 0.1g were obtained. A significant amount of long period energy was observed on distant seismograph records. The Brisbane seismograph station, located 630 km from the epicentre, recorded 8 s period energy lasting for longer than 2 min.

Macroseismic data includes over 30000 "felt reports". Modified Mercalli intensity (MMI) values assigned to these reports ranged from MMI VIII to IX in Newcastle, to MMI I representing several reports of buildings swaying at the Gold Coast (550 km distant) and in Melbourne (800 km distant). The area within which significant damage was sustained, corresponding to MMI VI to IX, extended from Newcastle south to Liverpool (Sydney, 135 km), north west to Scone (118 km) and Cassilis (200 km), and north to Gladstone (near Kempsey, 250 km). In the absence of strong motion data, the required engineering parameters must be obtained indirectly from assigned intensity values.

4.2 Ground Movement and Damage

Ground movements included a 50 mm settlement of the southern abutment to the Stockton bridge, and ground waves (11). Surveying of damaged buildings after the earthquake suggested building and ground settlements of up to 50 mm in Newcastle. No evidence of liquefaction was observed at the ground surface.

The majority of the building damage was associated with unreinforced masonry construction, particularly where lime mortar had been used and was in a poor state of repair. Much of the damage occurred at alluvial sites, particularly distant from the epicentre. More than 50000 buildings sustained damage as a result of the earthquake. These included commercial buildings of up to 8 storeys, low level apartment buildings, and dwellings. A number of buildings in the Central Business District of Newcastle suffered partial collapse. These included the Newcastle Workers' Club of reinforced concrete construction (where 9 fatalities occurred), and the Newcastle Returned Servicemans' League Club. Damage to a number of other buildings was sufficient for them to be condemned. These included the Junction Motel of reinforced concrete construction, apartment buildings incorporating a "soft-storey" at ground level for garages, and part of the Royal Newcastle Hospital.

Damage to masonry walls, including infill panels, cavity brick and brick veneer was widespread. Damage included in-plane shear, out-of plane peeling, and corner, racking and torsional failures. There was extensive evidence of masonry veneers not being adequately tied to the structure. Buildings affected included the Kent Hotel (where 2 fatalities occurred), schools, churches and shops. The collapse of parapets, verandas and free-standing chimneys was widespread. Cracked plaster walls, minor cracks in masonry, cracked and dislodged roof tiles, and cracks in concrete paths and masonry fences were observed throughout the damage area. While building services generally performed satisfactorily, damage to internal fittings was extensive. Damage to electricity supply switchyards caused by the earthquake resulted in the Newcastle area being without power for a number of hours following the earthquake.

4.3 Site Conditions

Brennan (12) reported that the Newcastle earthquake observations show a high degree of correlation between areas of significant damage and alluvial soil and/or fill, with about 80 % of the damage being located on saturated, unconsolidated sediments. With increasing epicentral distance, the damage on rock falls away and damage becomes almost entirely confined to alluvial areas. Based on damage levels in the near-field, peak ground accelerations as high as 0.25g were estimated.

The occurrence of amplification may be inferred from the observed level of damage, particularly in the far-field, given the relatively moderate size of the earthquake. For example, at Scone (MMI VI at 118 km distant), large cracks appeared in the masonry walls of buildings such as the swimming pool, the Parish Hall, and some houses, which were founded on the alluvial floodplain of Middlebrook. Elsewhere in the town, the earthquake was barely felt. The peak rock acceleration at Scone is estimated to have been less than 0.01g. At Cassilis (MMI VI at 200 km), a sandstone block chapel founded on recent alluvium suffered cracks through the walls and masonry blocks. The peak rock acceleration here was probably less than 0.005g. The unreinforced masonry Police Station at Gladstone east of Kempsey, and 320 km north east of the epicentre, suffered minor cracking. This building is located on the Macleay River floodplain and is the only masonry building in the town. The brick Children's Hospital at Liverpool (Sydney), 138 km south west of the epicentre, and built on the Georges River floodplain, suffered cracking sufficiently extensive to force its closure.

5. ASSESSMENT OF STRONG MOTIONS DURING 1989 NEWCASTLE EARTHQUAKE

5.1 Approach to Assessment

Chapman et al. (13) assessed the attenuation/amplification effects during the 1886 M_s 7.65 Charleston earthquake based on assigned intensities. Aki and Irikura (14) found a remarkably positive correlation between site-dependent, weak motion amplification and intensity, suggesting that intensity may be a more versatile seismic hazard parameter than the conventional peak ground acceleration. This is not too surprising since intensity is a direct, if qualitative, measure of the effect of the earthquake shaking reaching the ground surface. Attempts have also been made to predict site amplification based on surface geology. The younger the geology, the greater the site amplification tends to be. Borcherdt et al. (15) reported that amplification is quite well correlated with geological unit, shear wave velocity V_s and MMI. The combination most susceptible to amplification is fill and recent very soft to soft alluvium of low V_s (of the order of 130 $m.s^{-1}$), which on average may cause amplification of 5.7, and an increase of 2.4 intensity units.

On the basis of these observations, an approach involving assigned intensities and surface geology was adopted in the assessment of the strong motion during the 1989 Newcastle earthquake. This approach was combined with the mean attenuation relationship for a M_L 5.6 earthquake in this region.

5.2 Methodology and Results

Jorss and Wishart (16) grouped a significant sample of the preliminary macroseismic data collected by the Centre for Earthquake Research at the University of Queensland from the 1989 Newcastle earthquake (594 data points), according to identified surface geology. In particular, attention was focused on sites underlain by Quaternary alluvium (201 data points), and sites underlain by the older Palaeozoic sedimentary bedrock (105 data points). Much of the collected near-field data was excluded because the large volume of data collected in this area remains to be analysed. The selected data was plotted against epicentral distance, as shown in Figure 1. The right hand axis of Figure 1 is the peak ground acceleration normalised by g, to a logarithmic scale. Also included in Figure 1 are the upper and lower bounds for the alluvium and older bedrock sites, the estimated mean attenuation relationship for a M_L 5.6 earthquake in eastern Australia after Rynn (17), and a liquefaction lower bound after Williams (18).

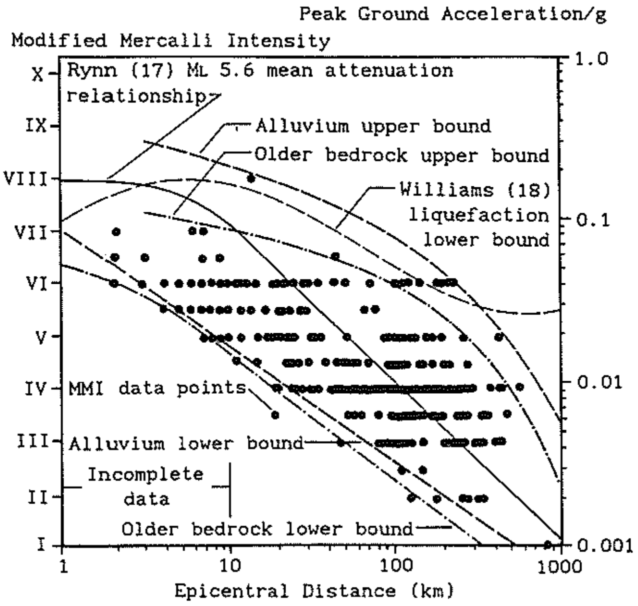

Figure 1 Selected Modified Mercalli intensity data from the 1989 Newcastle earthquake

It can be seen from Figure 1 that the alluvium upper bound is about one intensity unit above the older bedrock upper bound, while the alluvium lower bound is up to half an intensity unit above the older bedrock lower bound. It is also apparent from Figure 1 that the slopes of the bounds to the intensity data are considerably flatter than the slope of the attenuation relationship beyond an epicentral distance of 10 km. A few of the Newcastle intensity data points plot above the lower bound for the surface expression of liquefaction. In the near-field, intensities of up to MMI IX were assigned (not plotted in Figure 1). This corresponds to a peak ground acceleration approaching 0.4 g. About 10 km from the epicentre, limited intensity data suggest a peak ground acceleration approaching 0.2 g, dropping to 0.04 g with increasing epicentral distance. This acceleration level persists to about 230 km from the epicentre.

Taking the mean attenuation relationship to be representative of peak bedrock accelerations for the 1989 Newcastle earthquake, and the alluvium upper bound to represent the maximum degree of amplification through soft soils, maximum amplification factors may be estimated as a function of epicentral distance. The results are plotted as a curve in Figure 2, in which the estimated amplification factors are seen to rise rapidly with increasing epicentral distance, before tapering off at large distances. By way of comparison, a simplified calculation may be carried out to estimate the likely amplification in the far-field caused by the Newcastle earthquake. In the Newcastle region, the shear wave velocity of the bedrock is typically about 3500 $m.s^{-1}$, and that of the overlying alluvial soil is typically about 35 $m.s^{-1}$. The densities of the two materials may be taken as 22 $kN.m^{-3}$ and 18 $kN.m^{-3}$ for the rock and soil, respectively. Allowing for the impedance contrast between the bedrock and overlying soil, in the far-field a maximum amplification of the order of $[(3500x22)/(35x18)]^{0.5} \simeq 11$ is indicated. Allowing for some loss of energy, say 35 %, a more realistic estimate might be about 7. These values are in reasonable agreement with the maximum plotted value of about 9.

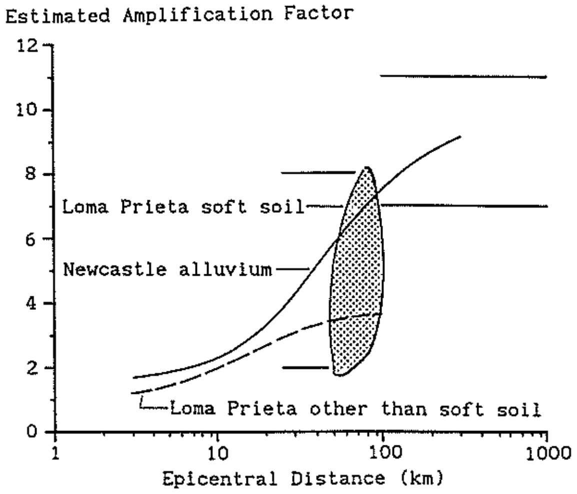

Figure 2 Estimated amplification factor versus epicentral distance

5.3 Comparison with Strong Motion Data Measured During 1989 Loma Prieta Earthquake

The acceleration data measured during the 1989 Loma Prieta earthquake provide an opportunity to check the validity of the approach adopted to assess the strong motion during the 1989 Newcastle earthquake. Seed et al. (19) reported that the Loma Prieta earthquake occurred when a segment of the San Andreas fault north east of Santa Cruz ruptured over a length of about 45 km, commencing at a depth of about 18 km near the centre of the rupture. It produced a magnitude of M_s 7.1 with a duration of 8 to 12 s, and damage over an area of about 7500 km^2, to a maximum of about 112 km from the epicentre. At least 62 fatalities occurred, with more than 2400 treated for injuries, and more than 12000 people displaced from their homes. Numerous aftershocks were recorded.

The mainshock caused numerous and widespread landslides, liquefaction and other soil failures surrounding San Francisco Bay and elsewhere, structural distress and failures in residential and commercial buildings, damage to non-structural elements and building contents, damage to critical road systems, and widespread disruption of utilities and other lifelines. More than 105000 homes, 500 apartment buildings, and 3500 businesses were damaged, with more than 1000 structures being condemned and demolished. Direct costs of up to US$10 billion, make it the most costly single natural disaster in United States history.

The affected region was unusually well instrumented with strong motion recorders (accelerometers), in the free-field, in buildings and on dams. The acceleration data collected confirmed the amplification of moderate and low amplitude bedrock motions by overlying weathered rock and, in particular, by overlying soft soils in the San Francisco Bay area (64 to 80 km from the epicentre). The latter preferentially amplified long period motions, and resulted in a massive concentration of damage (well over half) and loss of life (more than 80 %) at soft soil (typically loose sandy fill over deep, clayey alluvium) sites comprising less than 1 % of the affected area.

The moderate amplitude mainshock peak horizontal bedrock accelerations reaching the San Francisco Bay area were in the range 0.06g to 0.12g, and were amplified through the soil cover to peak ground surface accelerations estimated to be in the range 0.16g to 0.33g (2 to 3-fold). Amplification of the low peak bedrock accelerations reaching the area from the aftershocks was 4 to 8-fold. For two to four storey buildings such as those in the Marina District, there is further amplification through the structure of up to 2-fold as a result of resonant interaction with the amplified long period ground surface motions.

Seed et al. (20) compared well established (Ms 7.1) mean attenuation relationships for the western United States with peak ground accelerations measured on different ground conditions during the Loma Prieta earthquake. The Idriss (21) relationship is a good mean to the "rock" site and "stiff soil" site acceleration data. The Joyner and Boore (4) relationship is a little low to represent the mean to the "rock" site, "stiff soil" site and "deep soil" site acceleration data, but their mean ± 2 standard deviation curves bound the data well. Idriss (6) tended to favour the Joyner and Boore mean relationship. Peak ground acceleration data recorded at the surface of "soft soil" sites during the Loma Prieta mainshock and aftershocks plot well above both attenuation relationships, straddling the Joyner and Boore mean + 2 standard deviation curve. The Idriss mean relationship, the Joyner and Boore mean relationship and mean ± 2 standard deviation curves, and the Loma Prieta soft soil data cloud are shown in Figure 3. Also reproduced for comparison in Figure 3 are the curves plotted in Figure 1.

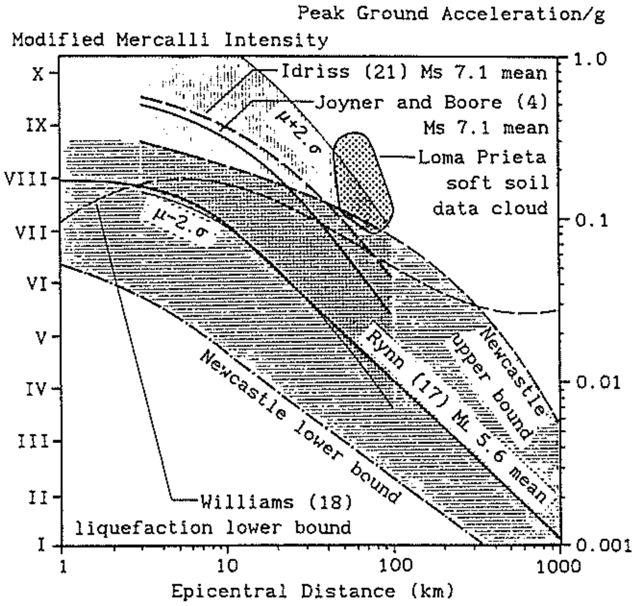

Figure 3 Comparison between Newcastle and Loma Prieta data

Conservatively (since the aftershocks to which some of the data apply were of much smaller magnitude than the mainshock) taking the Joyner and Boore mean attenuation relationship to be representative of peak bedrock accelerations for the Loma Prieta earthquake, the amplification factor through the soft soils may be estimated for each data point within the cloud. The results are shown as a data cloud in Figure 2. The cloud shows an amplification factor ranging from about 2 to about 8, in agreement with that reported by Seed et al. (19). The estimated Loma Prieta soft soil amplification factors are also of a similar order to those for the Newcastle region alluvium sites, estimated using a similar approach.

Again taking the Joyner and Boore mean attenuation relationship to be representative of peak bedrock accelerations for the Loma Prieta earthquake, the maximum degree of amplification through other than soft soil cover may be estimated from the upper bound to the measured acceleration data. The results are plotted as a curve in Figure 2, in which the estimated amplification factors are seen to rise with increasing epicentral distance, before tapering off at about 100 km. The trend of the curve is similar to that of the Newcastle alluvium curve, except that the stiffer ground to which the Loma Prieta data apply produce far less amplification than the soft Newcastle region alluvium, as would be expected.

The amplification factors estimated for the Newcastle region alluvium sites are plotted with the Idriss (6) median relationship between peak accelerations on rock and those on soft soil sites in Figure 4. The Newcastle estimates are in remarkably close agreement with the median relationship.

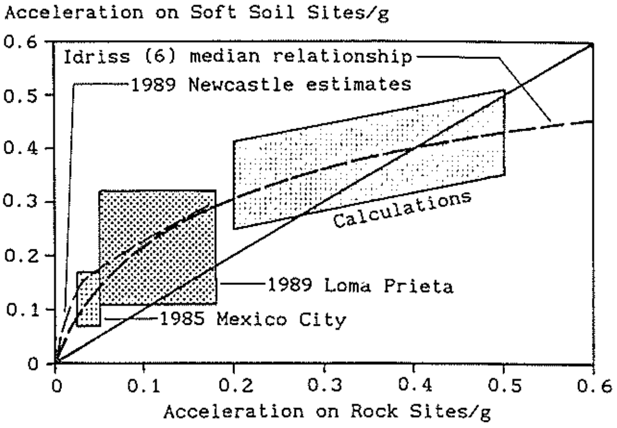

Figure 4 Comparison between Newcastle estimated amplifications and Idriss (6) median relationship

6. CONCLUSIONS

An assessment of the strong motion during the 1989 ML 5.6 Newcastle earthquake has been carried out using available macroseismic data from the earthquake, together with the mean attenuation relationship for the earthquake magnitude and region, and information on surface geology. The results obtained compare well with worldwide data analysed in a similar way, again emphasising the importance of site conditions and the very much greater hazard posed by continental earthquakes compared with plate margin earthquakes of the same magnitude. When the complete macroseismic database from the Newcastle event becomes available, more complete analyses will be carried out.

7. ACKNOWLEDGEMENTS

The author is indebted to the many colleagues whose freely given views and information were invaluable in formulating an understanding of the phenomenon of site amplification. These include Drs Rynn and Morris of The University of Queensland, Ted Brennan of Brisbane, Drs Byrne, Finn, Anderson and Campanella of The University of British Columbia, and Dr Jacobs of Columbia University. Special appreciation is extended to former students Nick Jorss and Vaughan Wishart at The University of Queensland for their dedication in collating and plotting the Newcastle intensity data.

8. REFERENCES

1. Okamoto, S. (1973). *Introduction to earthquake engineering*. Univ. of Tokyo Press.

2. Seed, H.B. and Idriss, I.M. (1982). *Ground motions and soil liquefaction during earthquakes*. Earthquake Eng. Research Inst. Monograph Series.

3. Stewart, W.P. and Campanella, R.G. (1991). Insitu measurement of damping in soils. *Proc. Second Int. Conf. on Recent Advances in Geotechnical Earthquake Eng. and Soil Dynamics, St Louis, Missouri*, Vol. I, pp. 83-92.

4. Joyner, W.B. and Boore, D.M. (1988). Measurement, characterization, and prediction of strong ground motion. *Proc. A.S.C.E. Geotechnical Eng. Div. Spec. Conf. on Earthquake Eng. and Soil Dynamics II - Recent Advances in Ground-Motion Evaluation, Park City, Utah*, Geotechnical Spec. Pub. No. 20, pp. 43-102.

5. Finn, W.D.L. (1991). Geotechnical engineering aspects of microzonation. *Proc. Fourth Int. Conf. on Seismic Zonation, Stanford, California*, Vol. I, pp. 199-259.

6. Idriss, I.M. (1990). Response of soft soil sites to earthquakes. *Proc. H.Bolton Seed Memorial Symposium*, Vol. 2, pp. 273-289. BiTech Publishers Ltd., Vancouver, Canada.

7. Whitman, R.V. and Algermissen, S.T. (1991). Seismic zonation in eastern United States. *Proc. Fourth Int. Conf. on Seismic Zonation, Stanford, California*, Vol. I, pp. 845-869.

8. Jacob, K.H. (1991). Seismic zonation and site response: are Building-code soil-factors adequate to account for variability of site conditions across the US? *Proc. Fourth Int. Conf. on Seismic Zonation, Stanford, California*, Vol. II, pp. 695-702.

9. Algermesson, S.T. (1983). *An introduction to the seismicity of the United States*. Earthquake Eng. Research Inst. Monograph Series.

10. Rynn, J.M.W. (1990). Introduction - Earthquakes and the Australian Community. *Proc. Fourth Earthquake Eng. Workshop, The Univ. of Queensland, Australia*, 9 pp.

11. Rynn, J.M.W. (1990). The 28 December 1989 Newcastle, Australia, earthquake. *Proc. Fourth Earthquake Eng. Workshop, The Univ. of Queensland, Australia*, 22 pp.

12. Brennan, E. (1990). Geological controls on damage patterns resulting from the 1989 Newcastle earthquake. *Proc. Fourth Earthquake Eng. Workshop, The Univ. of Queensland, Australia*, 9 pp.

13. Chapman, M.C., Bollinger, G.A., Sibol, M.S. and Stephenson, D.E. (1990). The influence of the coastal plain sedimentary wedge on strong ground motions from the 1886 Charleston, South Carolina, earthquake. *Earthquake Spectra*, Vol. 6, No. 4, pp. 617-640.

14. Aki, K. and Irikura, K. (1991). Characterisation and mapping of earthquake shaking for seismic zonation. *Proc. Fourth Int. Conf. on Seismic Zonation, Stanford, California*, Vol. I, pp. 61-110.

15. Borcherdt, R., Wentworth, C.M., Janssen, A., Fumai, T. and Gibbs, J. (1991). Methodology for predictive *GIS* mapping of special study zones for strong ground shaking in the San Francisco Bay region, CA. *Proc. Fourth Int. Conf. on Seismic Zonation, Stanford, California*, Vol. III, pp. 545-552.

16. Jorss, N.C. and Wishart, V. (1991). *Application of Newcastle earthquake data to Queensland*. Fourth year thesis, Dept. of Civil Eng., The Univ. of Queensland.

17. Rynn, J.M.W. (1988). The assessment of seismic risk in north eastern Australia. *Civil Eng. Trans., I.E.Aust.*, Vol. CE30, No. 2, pp. 45-56.

18. Williams, D.J. (1988). Potential engineering risks in the earthquake hazard to the east coast of Queensland. *Civil Eng. Trans., I.E.Aust.*, Vol. CE30, No. 5, pp. 307-316.

19. Seed, R.B., Dickenson, S.E., Riemer, M.F., Bray, J.D., Sitar, N., Mitchell, J.K., Idriss, I.M., Kayan, R.E., Kroop, A., Harder, L.F. and Power, M.S. (1990). *Preliminary report on the principle geotechnical aspects of the October 17, 1989 Loma Prieta earthquake*. Earthquake Eng. Research Center, College of Engineering, University of California at Berkeley, Report No. UCB/EERC-90/05.

20. Seed, R.B., Dickenson, S.E. and Idriss, I.M. (1991). Principal geotechnical aspects of the 1989 Loma Prieta earthquake. *Soils and Foundations*, Vol. 31, No. 1, pp. 1-26.

21. Idriss, I.M. (1985). Evaluating seismic risk in engineering practice. *Proc. Eleventh Int. Conf. on Soil Mechanics and Foundation Eng., San Francisco*, Vol. 1, pp. 255-320.