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STRUCTURAL RESPONSE AND DESIGN SPECTRA MODELLING: RESULTS FROM SOME INTRA-PLATE EARTHQUAKES IN AUSTRALIA

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ABSTRACT

Seismic studies of the Australian continent have shown that moderate to large earthquakes occur at a rate of two to three per year. Records from the intra-plate earthquakes demonstrate that they have particular characteristics, such as frequency content, peak acceleration and duration, and are different from similar sized earthquakes in inter-plate regions. Due to the lack of strong motion recordings of intra-plate earthquakes at small distance, synthetic seismograms have been produced to test the structural response of URM buildings for typical design earthquakes. A set of Linear Response Spectra derived from four records are compared with the Design Spectrum recommended in the Australian Loading Code. The dynamic analysis was undertaken of a modelled typical URM building during simulated intra-plate earthquake with magnitude similar to that of the 1989 Newcastle earthquake. The results indicate that although the code underestimates their intensity, moderate Australian earthquakes should not cause significant damage to well designed and detailed masonry structures.

KEYWORDS

Intra-plate Earthquakes; Response Spectrum; Australian Earthquakes.

INTRODUCTION

Global monitoring of seismicity reveals that even though the majority of earthquakes occur inter-plate, there are moderate and large earthquakes which occur within the plates and thus can significantly affect population centres. In the last 100 years, there have been 20 such earthquakes with magnitudes 6.0 or greater in continental Australia, and 2 or 3 earthquakes per year are recorded with magnitude 5.0 or more. With a few exceptions, the fault planes of the larger well-constrained Australian earthquakes are in the upper 10 km of the crust. The very deepest well-constrained focus was in the Northern Territory at the base of the crust at about 40 km depth (McCue *at al.*, 1993, 1995).

The focal mechanisms of Australian earthquakes have been studied by using either seismic wave inversion techniques or the first motion polarity method. They confirm the surface geometry of faulting and the notion that those earthquakes are caused by rock failing under compression, the direction of the principal stress axes oriented similarly within seismic regions but varying between regions.

Intra-plate earthquake mechanisms have different characteristics from inter-plate earthquakes. Earthquakes originating on plate boundaries are often strike-slip events, they may rupture a very large area and last for a considerable time, and they have substantial low frequency energy. Intra-plate earthquakes which occur in the Australian continent are constrained within the earth's crust and are generally of shorter duration (Morison and Melchers, 1995). Local factors such as the strength of the crustal rock, stress concentration, stress drop and level of stress may play a dominant role in the earthquake process. Typical earthquakes in continental interiors are thought to be associated with local high stress drop which agrees with assumption of short fault rapture lengths (Estava, 1974). As a consequence, the duration of high intensity earthquake ground motion is shorter and the frequency content shifted to shorter periods.

Intra-plate accelerograms recorded to date in Australia show that the strong ground motion lasts for just a few seconds; typical P and S phases are seen, the motion starts with 1 to 2 seconds of relatively large amplitude cycles then decay followed by 5 or 6 cycles of the peak amplitude and then rapid decay towards the end when low frequency surface waves dominate. Intra-plate earthquakes with relatively small magnitude can produce large peak accelerations and large ground velocities in the near-field region, and are thus especially interesting from an engineering point of view.

SEISMIC INPUT DATA

In 1990 the Federal Government partially funded a project to monitor seismicity near the major cities. In the first part, from 1992 to 1995, 34 digital accelerographs were purchased and distributed to Canberra and State capitals. Even in the short time since then a number of useful accelerograms have been recorded and an accelerogram database is being compiled at the Australian Geological Survey Organisation for seismic hazard assessment, dynamic analysis of structures etc. To date, only a few strong motion recordings exist for intra-plate earthquakes at short distances. On the base of those records, synthetic seimograms are produced here to test structural response at maximum ground motion near the epicenter.

Synthetic accelerograms can be computed in many different ways. One method is based on scaling up recordings of smaller earthquakes. Scaling using multiplication by a constant factor will give a higher amplitude, but will not change either the frequency content or the duration. This type is not appropriate for a large increase of magnitude because it would give a synthetic accelerogram that is too short and has insufficient low frequency energy, although the original non-stationarity is retained.

In the other method of superposition or Greens Function Method, the basic assumption is that a large earthquake can be simulated by the summation in time of a number of smaller earthquakes (Joyner and Borre, 1986). Each sub-event is considered to have a slightly different origin time to represent the propagation of a rupture along the fault plane, and then summed together to produce the synthetic record. This method can produce useful accelerograms if we find a suitable record for the sub-event and use realistic source rupture parameters for the event being simulated.

In the first example (Fig. 1, rec. 1), we used accelerograms from the event of 6 August 1994 when a magnitude 5.4 earthquake struck the NSW central coast only 20 km west of the epicentre of he 1989 earthquake at Newcastle which had a magnitude 5.6 (Jones *at al*, 1994). The epicentral region was near the town of Ellalong, and the ground motion was well recorded. For this purpose, we selected the closest site - North Lambton, 39km away, where free field instrument was installed on rock. Results from analysis of horizontal ground acceleration indicated that in a Kanai type attenuation relation, the magnitude scaling factor b and the distance exponent were lower than those from studies of large earthquakes in the Western US (Clough and Penzien, 1993). Extrapolation to epicentral distances was done using a regional relation between the peak ground acceleration and distance, giving a maximum acceleration of 0.15g. The observed average ratio between the peak vertical and the peak horizontal ground motion was 0.53, though it varied enormously.

In the second example (Fig. 2, rec. 2.), we used the aftershock of 29 December 1989 when a magnitude 2.3 earthquake shook Newcastle nearly 34 hours after the main event and from the same focal area. For the purpose of simulation with the Green's function method, we selected an accelerogram from the site at the University, about 20km away, where a free-field instrument was installed on rock.

Extrapolating to the stronger 1989 Newcastle earthquake, we assumed the defined source parameters for a rupture of 1.5km, and a magnitude exponent term in the spectral formula to be 1/3 (close to the high frequency constraint). We applied a two-step procedure; 275 sub-events were summed and we gradually increased the magnitude from 2.3 to 5.6. An alternative estimate of velocity was obtained by overlaying intensities, but gave unrealistically high peak horizontal bedrock ground velocities, which indicated that linear extrapolation to very close distances in not always successful. Hence, to test structural response to the strongest Australian intra-plate earthquakes, we formed synthetic near-field seismograms using locally recorded accelerograms.

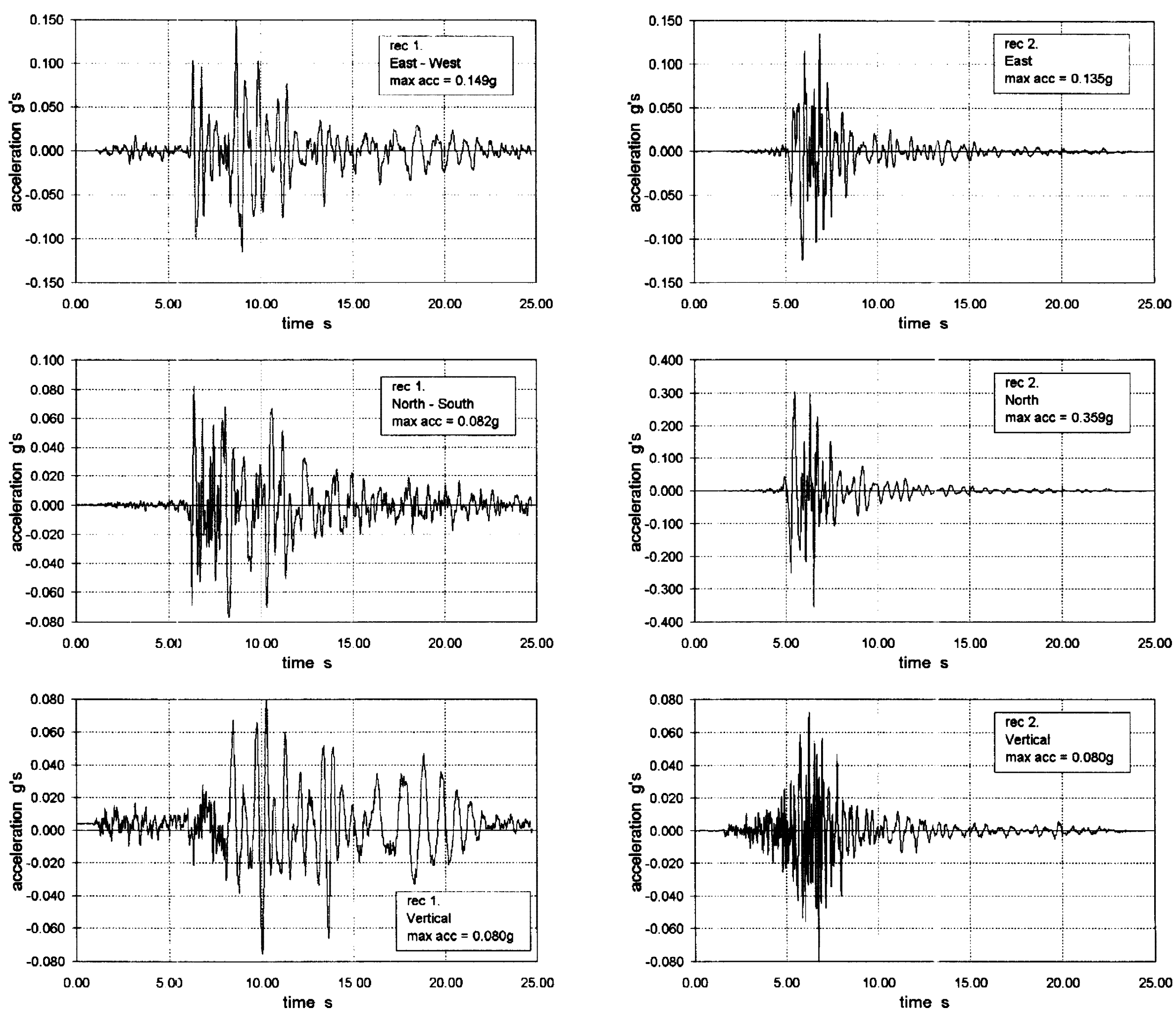

Fig. 1. Normalised Intra-plate Earthquake Record
(rec.1: Ellalong, NSW, 1994, M=5.4; rec. 2: Newcastle (aftershock), NSW, 1989, M=5.6)

DESIGN RESPONSE SPECTRUM

In order to investigate the implication of the Australian intra-plate earthquakes on design practice, a set of Response Spectra was developed. The Spectral curves were derived from the time history records discussed above. Since the vertical component is of much lesser importance for the seismic stability of buildings, only the horizontal components of the two earthquakes will be considered. In total, four time history records were obtained and will be considered.

From this set of four records, the N-S component of the synthetic record generated from the Newcastle aftershock of 29 December 1989 has the greatest peak acceleration, equal to 3.52 m/s^2. For this record a Linear-Elastic Response Spectra for a standard series of damping ratios is developed (Fig. 2).

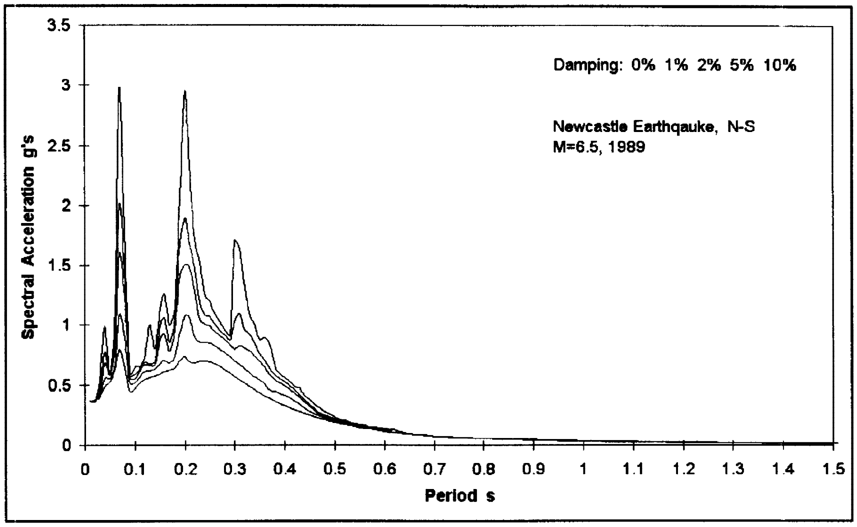

Fig 2. Response Spectra of Newcastle Earthquake, N-S, 1989

For the lower damping values, the Spectral Curves show a group of three clear peaks in the period range from zero to 0.4 seconds. For higher damping values, 5% and 10%, the Spectral Curves exhibit a smoother shape. This record confirms the expectations of a high frequency content for intra-plate earthquakes.

This frequency content may induce higher damage in stiff structures, such as low-rise masonry or concrete buildings. This is especially important for Australia, where a great majority of the domestic and commercial buildings are made of masonry, typically with double-leaf brick masonry walls in traditional construction. Modern practice is to use lighter brick-veneer construction with a timber frame. According to a recent extensive study, a typical single storey building in Australia has a natural period within the range of 0.06s to 0.07s (Klopp and Griffith, 1993). These values were measured at a very low excitation levels. It may be expected that for a higher excitation level, some cracks in the masonry may develop. Consequently the stiffness will drop and the natural periods may rise to 0.1s or more. This will put the masonry buildings within the region of the highest spectral values.

The intensity of the Spectral Accelerations of the recorded events is generally lower than that of inter-plate earthquakes. We next compare the Design Spectra recommended in the Australian Design Code and the Spectral curves from recorded seismic events. The Australian Earthquake Design Code AS 1170, Part 4, was introduced in 1993. The code is based on a modern approach and recognised design principles. The main design approach is based on the Equivalent Static Force method, although other approaches such as dynamic analyses based on Time History analysis or Spectral Response are also allowed. For buildings of higher importance or for building exposed to a potentially higher hazard, the Code recommends a Dynamic Response analysis, implementing either Spectral Method or Time History analysis. The seismic forces may be determined by any of the mentioned approaches, but the total base shear can not be less than the total force determined by the Equivalent Static Force method. The Spectral Curve in the Code (AS 1170.4) is given by the following expressions:

$$S_v = \frac{1.25 \cdot S}{T^{2/3}} \quad \text{and} \quad S_v \leq 2.5$$

where:

S_v - spectral value in g's
S - site factor (a typical value is S=1.0)
T - period in seconds

The Spectral Curve is for a damping ratio of 5%. The Spectral Values are then scaled by the relation of the acceleration coefficient, the importance factor and the structural response factor, given as:

$$S_f = \frac{a \cdot I}{R_f}$$

where:

S_f - scaling factor
a - acceleration coefficient (note: for the Newcastle region, a=0.11)
I - importance factor (a typical value for I=1.0)
R_f - structural response factor (for unreinforced masonry $R_f = 1.5$)

If we consider a typical unreinforced masonry building located in Newcastle the scaling factor will be equal to 0.0722. Multiplying by the maximum spectral value of 2.5g, we produce a maximum spectral acceleration of 0.18g. This Design Acceleration Spectra is compared with spectral curves from all four horizontal components of ground motion described above. The spectral curves for periods of up to 1.5 seconds are shown in Fig. 3. It is observed the all four records have clear peaks at periods below 0.7 seconds. As expected, the higher frequencies are dominant in the overall frequency content.

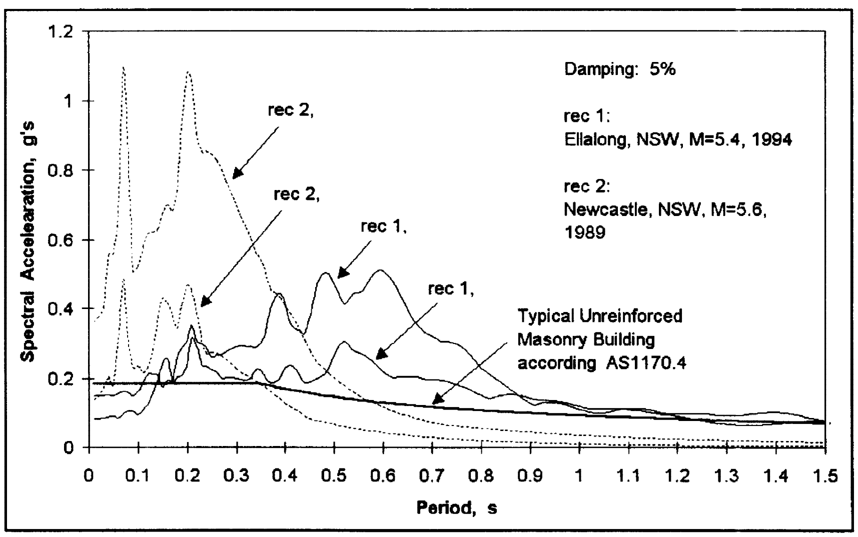

Fig. 3 Response Spectrum of Four Intra-Plate Records

When the spectral values are considered, a significant difference is observed between the values recommended by the Design Code (AS1170.4) and the actual spectral curves. This difference suggest that the spectral values at short period recommended by the Code significantly underestimate the intensity of Australian earthquakes in the epicentral area. Non-ductile building designed to the Australian Code may not be conservatively designed.

SAMPLE BUILDING

To investigate the response of a typical unreinforced masonry building exposed to an Australian earthquake, a model two storey unreinforced masonry building with three load bearing walls is considered with the earthquake acting parallel to one orthogonal direction of the building (Jankulovski *at al.*, 1994). The wall thickness is 230 mm. The material properties are as follows:

Material Density:	1950 kg/m^3
Shear Bond Strength at Joints:	0.70 MPa
Tensile Strength:	1.00 MPa
Compressive Strength:	15.0 MPa
Modulus of Elasticity:	2,000 MPa
Shear Modulus:	500 MPa
Damping Ratio:	7.0%

It should be emphasised that the values of the properties listed above, are not the values used traditionally in the design procedure. They are mean values compiled from a large set of experimental data. They represent the most likely values of the material properties without any safety factor. This approach is believed to provide more realistic results in a dynamic analysis. All required input data for the analysis are given in the table below:

Storey	P_y kN	P_u kN	D_y mm	D_u mm	K_1 kN/mm	K_2 kN/mm	Mass t
2	1377	1693	1.79	2.68	769	355	92.8
1	1074	1074	1.79	1.79	600	0	92.8

Where:

P_y - Horizontal Force at First Yielding (Elastic Limit)
P_u - Ultimate Horizontal Force
D_y - Horizontal Displacement at First Yielding
D_u - Horizontal Displacement at Ultimate Force
K_1 - Initial Storey Stiffness
K_2 - Tangent Storey Stiffness

The above values were evaluated using the Ultimate Capacity approach. This approach is broadly used in the analysis of masonry buildings and is extensively reported in the literature (Jankulovski *at al.*, 1994, Tomazevic and Zarnic, 1985). For each wall, four potential failure modes were considered: sliding, diagonal shear, bending and overturning. For each failure mode an ultimate force is calculated. The lowest value of the ultimate forces determines the failure mode for each wall. Then, using a specific ductility factor for the most likely failure mode an ultimate deformation is calculated. Afterwards, the force-displacement diagram for each wall is defined.

Storey force-displacement is calculated as a summation of force-displacement diagrams of all the walls on that particular storey. Then, the storey force-displacement diagram is approximated as a bi-liner relationship. For each storey only two points on the diagram are required. In the table above, the first yield point is defined by the values of P_y and D_y, and the ultimate point is defined by P_u and D_u. These values are used for a non-linear dynamic response analysis of a shear-type model. The dynamic analysis was based on a well established step-by-step explicate integration method detailed by Clough and Penzied, 1993.

In this analysis the N-S component of the synthetic record from the Newcastle aftershock of 29 December 1989 is used with its maximum acceleration of 3.52 m/s^2. The analysis consists of a Non-Linear Dynamic Response Analysis of a shear type building model. The maximum relative story displacements during the earthquake were calculated as: 0.48mm and 1.20mm for the second and first storey, respectively.

The results indicate that the structure will remain in the elastic range for the duration of the earthquake. For this particular excitation only minor damage in the form of micro cracking may be expected. This example confirms the observation from the Newcastle Earthquake, that well designed structures can remain virtually intact. Most of the damage was due to poor workmanship and material degradation, eg. corrosion or lack of wall ties. This example indicates that a well designed and constructed masonry building should be able to resist a typical moderate magnitude Australian earthquake without significant damage. Thus, no special measures need be undertaken to increase the strength of new well designed and constructed masonry buildings when their earthquake resistance to the 500 year earthquake is considered.

CONCLUSIONS

Records of Australian intra-plate earthquakes have shown different characteristics (frequency content, peak acceleration and duration), when compared with other events from inter-plate regions. The lack of quality strong motion records of intra-plate earthquakes at short distance initiated the usage of synthetic seimograms as a means of testing structural response for maximum expected parameters. In the tests, we considered the near-field synthetic records of likely intra-plate earthquakes with strong ground motions with duration of several seconds.

It was observed that the Spectral Design Curve recommended in the Australian Design Code AS1170.4, is significantly lower than the potential seismic events. Based on the results of a dynamic response analysis performed on one model masonry building it could be concluded that such Australian earthquakes would not cause significant damage to well designed and detailed masonry buildings. This fact suggested that no special measures should be undertaken to increase the earthquake stability of typical masonry buildings in Australia. Well detailed buildings in combination with good workmanship should be sufficient to provide adequate earthquake resistance for unreinforced masonry buildings in Australia.

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