

## **Recent developments in the research and practice of earthquake engineering in Australia**

***JL Wilson<sup>1</sup> and NTK Lam<sup>2</sup>***

<sup>1</sup> Swinburne University of Technology

<sup>2</sup> The University of Melbourne

### ***Abstract***

This paper presents multi-disciplinary facets of earthquake engineering research and developments in Australia over the past decade. Past and current research into seismic activity modelling and the associated challenges is first described. The Component Attenuation model (CAM) that provides estimates for the seismic displacement demand in regions lacking strong motion data is then introduced along with other models developed by conventional methods. Research into the seismic performances of typical Australian construction which incorporates the use of unreinforced masonry, steel and concrete has been summarized together with a brief report on current activities with risk modelling and the earthquake loading standard. A new two-tier displacement based approach for assessing the seismic performance of structures is presented along with future trends in earthquake engineering.

### ***Introduction***

Over the past 100 years, Australia has been subject to, on average, one earthquake event exceeding M5 every year and one event exceeding M6 every five years (McCue et al, 1995). Most of these earthquake events did not cause casualties but there has been noticeable damage to infrastructure including railway lines and gas mains (eg. earthquake at Meckering, Western Australia and at Tennant Creek, Northern Territory). The location of historical earthquakes obtained from archive sources has been central to the modelling of seismic hazard across the continent.

The first seismic design Standard (AS2121) was introduced in Australia in 1979. Every aspect of seismic design provisions ranging from the definition of the spatial distribution of seismic hazard, loading requirements and rules for design and detailing was covered in one document. However, because most cities were located in zone zero there was little impact from this standard on the engineering profession.

An earthquake event of mere M5.6 which occurred at Newcastle, New South Wales (some 100km northeast of Sydney) in December 1989, cost 11 lives and resulted in widespread damage to unreinforced masonry walls (Melchers, 1990). This was by far the most significant earthquake event in Australian history. Ironically, Newcastle was designated seismic zone zero in AS2121(1979).

Earthquake engineering research in Australia was limited to seismic activity modelling and seismological monitoring until the late 1980s when research into the response behaviour of structures in seismic conditions was first undertaken at the University of Melbourne. The current Australian Earthquake Loading Standard AS1170.4, which was introduced in 1993, was essentially based on the 1991 version of the Uniform Building Code (UBC, 1991) of the United States.

The 1989 Newcastle earthquake prompted intensive multi-disciplinary research on earthquake engineering, with Geoscience Australia (then Bureau of Mineral Resources) being the major centre of investigation into the seismological aspects, and the University of Melbourne into the structural engineering aspects. Investigations into the seismic performances of unreinforced masonry walls have primarily been based at the University of Adelaide. With strong and sustained collaborations between these three centres along with numerous other groups across the country, studies targeted initially at Australian conditions, have been developed into generic studies for worldwide applications in

regions of low and moderate seismicity. The formation of the Australian Earthquake Engineering Society in 1990 and the introduction of an annual technical conference provided an opportunity to exchange information and collate research findings. Strong links between these centres and other international centres on mainstream earthquake engineering research in New Zealand, Canada and USA have been established. Importantly, strong international research collaborations have also been formed with overseas institutions from regions with similar levels of seismicity, namely South China, Italy and Singapore.

This paper presents an overview of Australian earthquake engineering research activities and their outcomes.

### ***Seismic activity modelling***

In Australia, little is known of the rate of seismic activity of individual faults. Consequently, earthquake sources have been modelled as "polygonal areal source zones" in the seismic hazard analysis procedure (Gauil 1990). The size and geometry of these source zones have been delineated in accordance with information of localizing geological structures or "groups of faults" that have the potential of generating future earthquakes. Many of the decisions in delineating the zone boundaries were dictated by subjective judgement. The location of historical earthquakes is strongly reflected in the developed zonation model due to infrequent occurrence of earthquakes of engineering significance and the very limited time-window in the historical events database. Consequently, many "bulls-eye" type contours which coincide in location with recorded earthquake epicentres are displayed on the seismic hazard maps of the country (refer hazard maps in AS1170.4, 1993).

The Kernel method which expresses seismic activity density as a continuous function in space (eg. Woo 1996) has been applied recently to Australia (Stock 2002a&b). This new approach is in contrast to the traditional approach of modeling seismic activities as discrete polygonal sources which have distinct boundaries. A Kernel function is used to "smear" a historical epicentre into the surrounding area. This smoothing process will suppress, if not completely eliminate, the "bulls-eye" effects mentioned previously.

Another important shortcoming with the historical database is the very limited number of recorded large magnitude events. Consequently, the recurrence behaviour of large magnitude earthquakes has been predicted by extrapolating observations from the smaller magnitude events. The paucity of seismicity data can be compensated by using relevant information gained from on-going studies in the area of paleoseismology (or seismic geomorphology) which is the branch of science devoted to studying pre-historical earthquake activity based on making observations from landforms. In Australia, there is a wealth of geomorphic evidence associated with seismic activities, but there have been very few detailed investigations. Information on the orientation of stress fields from oil exploration investigations undertaken by Denham also provides useful information on the failure susceptibility of known faults. The study of seismic activities is not limited to investigating faulting activities and slip-rates. Landform evolution on a much larger scale (eg. mountain building) has been studied to gain insight into the underlying tectonic processes which drive seismic activities. Evidence for mountain building could come from extensive geophysical data that measures radioactivity and magnetic fields of exposed soil and rock. Rocks of different ages and types display different levels of radioactivity and magnetic properties. Faults and uplift which bring older rocks to the surface or bury younger strata can be detected through such measurements. Intense mountain building in southeastern Australia over the past 10 million years has been detected from such an approach (Sandiford et al, 2003).

Recently, high resolution digital elevation models (DEM) have emerged as important tools for finding and characterizing earthquake related geomorphology and particularly fault scarps (Clark 2005). The method is advantageous for locating fault scarps over large or remote areas and can provide a basis for imposing restraints on seismicity

models. The mapping of geophysical quantities such as gravity fields, magnetic fields and heat flows have also provided very relevant information on the underlying tectonic processes which drive intraplate seismic activities (Brown 2003).

Numerous modelling approaches involving input from a range of disciplines have been described. The spatial distribution of seismic activity within Australia as inferred from seismological observations and from geo-morphological and paleo-seismological studies are based on events of different magnitude range. Thus, comparative studies need to be undertaken to identify major anomalies. Overall, the challenge is in reconciling differences between contributions from different modelling approaches and integrating them into a robust seismic model that is representative for the Australian continent.

### ***Attenuation modelling***

Intensity attenuation relationships were first developed for different parts of Australia by Gaull (1990) using iso-seismal maps. Such valuable information on intensity has been translated into approximate peak ground velocity (PGV) information using the well known transformation of Newmark (1971). The current seismic hazard maps for Australia (in AS1170.4, 1993) are based on those established benchmarks. However, intensity data only provides overall indication in the intensity of the ground shaking and not its frequency properties which characterize the shape of the response spectrum. The potential for an earthquake to displace a structure and cause damage and instability, depends on both the PGV and the frequency properties of the ground shaking. The PGV parameter alone is not fully indicative of the potential seismic hazard in engineering terms since the displacement demand of an earthquake increases with earthquake magnitude for a constant PGV. The potential hazard of an area can be characterized more effectively using design earthquake scenarios expressed in terms of magnitude-distance combinations. For this reason, the realistic modelling of the seismic hazard depends on the accurate representation of the seismicity of moderate and large magnitude events as well as the frequency dependent (response spectrum) attenuation behaviour of the earthquake.

During the 1990s, the Australian Geological Survey Organisation (AGSO, now renamed Geoscience Australia) undertook a detailed study of 13 accelerograms measured at rock sites from reverse thrust fault events with magnitude ranging from 5.4-6.6 (Somerville, 1998). Records were normalised to a PGV of 50mm/sec, and the normalised design response spectrum (NDRS) model proposed from this study has been illustrated in tripartite form. However, Somerville's model did not directly account for the variation in the regional geological conditions across the Australian continent as described by Dowrick (1995). The Component Attenuation Model (CAM) was soon developed to allow for variations in regional conditions. CAM was developed initially in Australia and was first published internationally in Lam (2000a-c). In CAM, response spectrum is defined as a product of factors representing various source, path and site effects. CAM has now been developed into a generic tool for international applications (refer review by Chandler 2001; Hutchinson 2003; Lam 2003 and 2004). CAM is essentially a tool by which information obtained from local seismological monitoring studies is utilized to construct a representative response spectrum for direct engineering applications. Through the CAM framework, contributions from Australian seismological research (eg. Allen 2003; McCue 2003; Wilkie 1995; Gaull 1990) can be translated into valuable information for response spectrum modelling for the country.

Remarkable consistencies between the Intensity Model of Gaull, the empirical intraplate model of AGSO and CAM have been demonstrated recently (Lam 2003). Meanwhile, shortcomings of employing overseas attenuation models (eg. Toro 1997) for applications in different regions within Australia have been highlighted. A response spectrum model recommended for Australia by Somerville 1998 and Wilson and Lam 2003 (based on CAM) has been incorporated into the draft for the new Australian Standard for earthquake actions.

## **Site response modelling and microzonation**

The significance of site effects was confirmed by observations from the 1989 Newcastle earthquake in which the most severe damage was found in areas covered by soft soil sediments (Institution of Engineers report, edited by Melchers 1990). Research into site effects can be divided into two main streams, namely (i) site classification and microzonation and (ii) soil amplification.

Studies on site classification and micro-zonation were based either on (i) identifying regolith properties and their potential response behaviour using information obtained from seismic cone penetrometer tests (eg. Dhu 2002) or (ii) identifying site natural period using borehole information (eg. Lam 1999) or the well known Nakamura technique (eg. Turnbull 2003). These conventional modelling techniques were applied to numerous cities around Australia including Newcastle and Lake Macquarie in New South Wales; and Bundaberg and Hervey Bay in Queensland.

A more advanced site identification technique was developed recently by Asten who makes use of background noises generated by meteorological and cultural sources, with machinery and vehicle traffic being the principal sources at periods of interest. This seismic energy propagates primarily as surface waves which are then analysed by what is known as the Spatial Autocorrelation (SPAC) method (Asten 2002; Asten, 2003). The shear wave velocity profile of the site could be determined using the SPAC method down to a depth which is comparable to the diameter of the geophone array (typically in the order of 50-100m but could be increased as desired). The SPAC technique, which is still in the early stage of its development as a practical engineering tool, has been put into test in a recent study undertaken in Perth (Asten 2003).

Studies on soil amplification were undertaken as part of the research into the regolith identification procedure described above (Venkatesan 2002, 2003 and 2004). The analyses employed either the stochastic equivalent-linear methodology (Electric Power Research Institute, 1993) or the non-linear one-dimensional shear wave analysis methodology using the well known program SHAKE (Idriss 1991). A significant development in the study of soil amplification is the modelling of displacement demand in conditions where seismic waves entering flexible soil layers are trapped between the soil surface and the high impedance contrast interface with the underlying bedrock. When conditions pertaining to resonance behaviour are developed, the displacement demand of the earthquake is particularly amplified at the "period of resonance" which is often well correlated with the natural period of the site. Structures with an initial (elastic) period lower than the site period are potentially at risk given that the natural period of a structure tends to lengthen as a result of deterioration in the structural strength and stiffness during the earthquake. The displacement demand on a flexible soil site can be particularly sensitive to the magnitude-distance combination of the earthquake due to the changes in frequency content and duration of the rock motion. The modelling of this high amplification phenomenon has been described in international research literature and incorporated into the CAM framework (refer Lam 2001; Chandler 2002; Lam and Wilson, 2004).

## **Structural response research**

This section provides a brief overview of a number of research studies that have been undertaken in Australia. The majority of the studies focus on the post-elastic performance and the response of Australian structures which typically have been designed for gravity and wind loading without consideration of seismic excitation. Research has been focussed on assessing the overstrength, failure patterns, displacement ductility and more recently the displacement capacity of different structural members, sub-assemblages and systems using both experimental and analytical techniques.

Buildings with soft storeys are well known to be particularly vulnerable to collapse and severe damage under earthquake excitation. Despite this, buildings possessing soft

storey features are commonly found in low to moderate seismic countries such as Australia. A research program has been undertaken to assess the axial load, lateral force and displacement capacity of reinforced concrete soft storey buildings. The displacement model accounts for the effects of axial compression, flexure, shear, column end rotation, foundation flexibility and plastic hinge formation. An experimental program to evaluate the accuracy and reliability of the analytical model is currently in progress (Rodsir 2003). The studies indicated that many buildings with soft storeys failed with limited ductility in flexure (rather than brittle shear failure) with storey drift capacities in the order of 2%. A comparison of the displacement capacity with the seismic displacement demand suggested that many soft storey buildings on rock and shallow soil sites would survive earthquakes with return periods in the order of 500 years.

Griffith (2003) has developed an innovative retrofit technique for improving the drift capacity of soft storey structures. The technique involves attaching steel or FRP plates to the flexural faces of columns using bolts. Tests have indicated that retrofitted columns develop drift capacities in excess of 2.5% with numerical models suggesting that 10% drift capacities could be possible.

An extensive experimental and analytical research program has been undertaken investigating the seismic performance of reinforced concrete wide band beam structures (Stehle 2001; Abdouka 2002). The sub-assembly testing research indicated that such structures designed for gravity loading using the minimum detailing requirements in Australia had drift capacities in the order of 2.5% before the lateral strength capacity is reduced. An innovative method of de-bonding the continuous top reinforcement in the band beam adjacent to the column demonstrated that the damage levels associated with large drifts could be significantly reduced.

The performance of concentrically braced steel frames (CBF) designed for elastic wind loads with no consideration of seismic loading was investigated (Wallace 2002). In particular the connections between the diagonal braces and the columns were studied to investigate the failure mechanism and overstrength. The research findings indicated that the connections were typically weaker than the members with an overstrength factor of the welded connections in the order of 1.5. Failure was typically initiated by low cycle fatigue cracking in the weld resulting in limited displacement capacity of the CBF system. A cost-effective retrofit measure to improve the ductility and drift capacity was briefly investigated and showed some potential. The retrofit measure involved introducing a structural fuse into the brace by a deliberate localised weakening of the member away from the connection to encourage local yielding rather than brittle fracture of the weld connection.

An innovative connection has been developed by Goldsworthy for connecting steel beams to concrete filled steel tube columns (CFT) using blind bolts (Yao 2005). The cyclic behaviour of this connection is the subject of an on-going industry funded research project that involves extensive laboratory testing and non-linear finite element modeling.

The behaviour of low rise precast concrete load bearing panel structures was investigated by Robinson (1999). These precast structures which are very common and popular for apartment buildings are characterised by having connections much weaker than the precast panel members. A study of this form of construction concluded that the better detailed connections allowed a limited ductile mechanism to develop resulting in the in-plane rotations of the panel members and a drift capacity in the range of 1-3% depending on the depth of connection embedment in the floor slab.

The behaviour of domestic structures (plasterboard lining with brick veneer external cladding) to lateral loads has been extensively investigated by Gad (1999). The studies indicated that the non-structural plasterboard contributes significant lateral strength to the overall system. In contrast, the brick veneer contributes negligibly to the lateral strength and is vulnerable to collapse from out-of-plane shaking depending on the condition of the brick ties. This study has been recently extended to investigate the damage thresholds of such construction under low level blast vibrations (Gad 2004).

An innovative displacement based technique for assessing the out-of-plane response of masonry construction has recently been developed by Griffith and the authors (Doherty 2002, Lam 2003 and Griffith 2004, 2005). The traditional force based methods are shown to be overly conservative and unreliable in predicting the failure of masonry walls. The displacement based procedure uses a tri-linear relationship to characterise the real non-linear force-displacement behaviour of a masonry wall and has been substantiated from an extensive experimental and complementary analytical program.

An investigation into the behaviour of adobe mud-brick construction has been undertaken by Dowling using extensive shaking table testing (Dowling 2004). The annual rate of fatalities and injuries from earthquake events is dominated by people living in adobe construction. The project focuses on low cost and low technology improvements for developing countries such as reinforcing the corners and mid-spans of walls with bamboo and other materials and the provision of a ring beam at roof level.

The response of tall reinforced concrete chimneys to earthquake excitation was investigated by Wilson (2002, 2003). These structures were historically very conservatively designed on the assumption that highly tuned dynamically sensitive cantilevers were inherently brittle. The experimental tests and analytical studies indicated that chimneys possess some ductility if designed appropriately. Such structures were best designed using modal analysis techniques and the elastic loads could be reduced by a structural response factor of  $R=2$  to allow for inelastic response, with significant cost savings.

Several analytical studies investigating the overall behaviour of structural systems have been undertaken. These studies have investigated: the ductility reduction factor in the seismic design of buildings (Lam 1998), equivalent damping ratios in reinforced concrete frame buildings for incorporation into the substitute structure method for seismic displacement response predictions (Edwards 2003) and the inelastic torsion response of buildings using a displacement based approach (Lumantarna 2003).

### ***Risk modelling***

Geoscience Australia has undertaken an extensive all-hazards risk study for selected Australian cities using GIS in a project termed 'Cities'. The earthquake aspects of the study involved field surveys to document the vulnerability characteristics of a representative sample of buildings and site studies to evaluate the soil conditions. Australian damage models based on the capacity spectrum method were then developed from heuristic studies of 'experts' and economic losses estimated using the HAZUS framework and the results displayed using the GIS model. Monte Carlo simulations were undertaken to consider the various combinations of magnitude, location, attenuation, soil amplification and building damage curves. The city of Newcastle, which experienced the M 5.6 in 1989, was the initial city studied and the results showed that the annualised loss was in the order of 0.04% or around \$12 million per annum (Dhu 2002).

Reinsurance purchased by Australian companies is dominated by the need to protect against catastrophic loss from property damage caused by earthquakes. In excess of \$100 million is paid annually to reinsurance companies to cover earthquake losses. The amount of reinsurance purchased is based on earthquake risk modelling and currently there are significant differences in the models being used. Walker (2003) recommends that a national consensus is required to develop the best assumption for modelling earthquake occurrence, attenuation, soil amplification and damage curves. Such information would have direct benefits to the insurance industry and Government agencies involved in emergency management and building regulations.

## Earthquake loading standard

The current Earthquake Loading Standard (AS1170.4) was released in 1993 and the updated version is due for release in 2006. Originally the updated version was to be a joint and harmonised Standard with New Zealand, however severe difficulties developed during the drafting process. The largest challenge was how to combine the existing New Zealand Standard developed for a high seismic country with that of Australia where the design practices were quite different and the Standard reflected that of a low to moderate seismic country. In addition, some cities in each country had similar levels of seismicity (eg. Auckland has a seismicity level similar to Melbourne and Sydney). After much deliberation it was decided in 2003 to develop separate Earthquake Loading Standards but to use similar notation where possible.

The 2006 Australian Earthquake Loading Standard is similar in layout to the 1993 edition but has been significantly simplified and updated. Most structures will now have to be designed for some earthquake actions to ensure minimum levels of robustness. The structural response factors ( $R_f$  factors) have been standardised (refer Table 1) and the designer is able to use a non-linear push-over curve to provide a better estimate where required (refer Section 8). The material standards have also been updated over the past decade with improvements to the base level of detailing particularly concrete structures to improve inherent robustness and toughness.

System	Ductility ( $\mu$ )	Over-strength ( $\Omega$ )	$R_f = \mu \times \Omega$
URM	1.25	1.3	1.6
Limited Ductile	2	1.3	2.6
Moderate ductile	3	1.5	4.5
Ductile	4	1.5	6

Table 1: Revised ductility and over-strength factors in AS1170.4 (2006)

The design response spectra have also been significantly updated with a better estimate of the response acceleration, velocity and importantly displacement for a given location and site (Wilson and Lam 2003). The design response spectra have been reproduced in Figure 1 in the form of an ADRS plot (acceleration-displacement response spectrum which has the advantage of simultaneously indicating the acceleration (force) and displacement (drift) demand) for a zone factor (or acceleration coefficient) of  $Z=0.08$  (or  $PGV=60$  mm/sec) which applies to major cities in southeastern Australia including Sydney, Melbourne and Canberra. The velocity and displacement demand parameters:  $RSV_{max}$  and  $RSD_{max}$  (or PDD) estimated for different return periods and site classes have also been listed in Tables 2a and 2b for  $Z=0.08$  and  $Z=0.08 \times 1.8=0.14$ . The site factors listed in Column 2 of the table were inferred from the response spectra stipulated in AS1170.4 (2006). The demand parameter values for the 2500 year R.P. were obtained by multiplying the 500 year R.P. estimated demand values by a factor of 1.8 as recommended in AS1170.4 (2006).

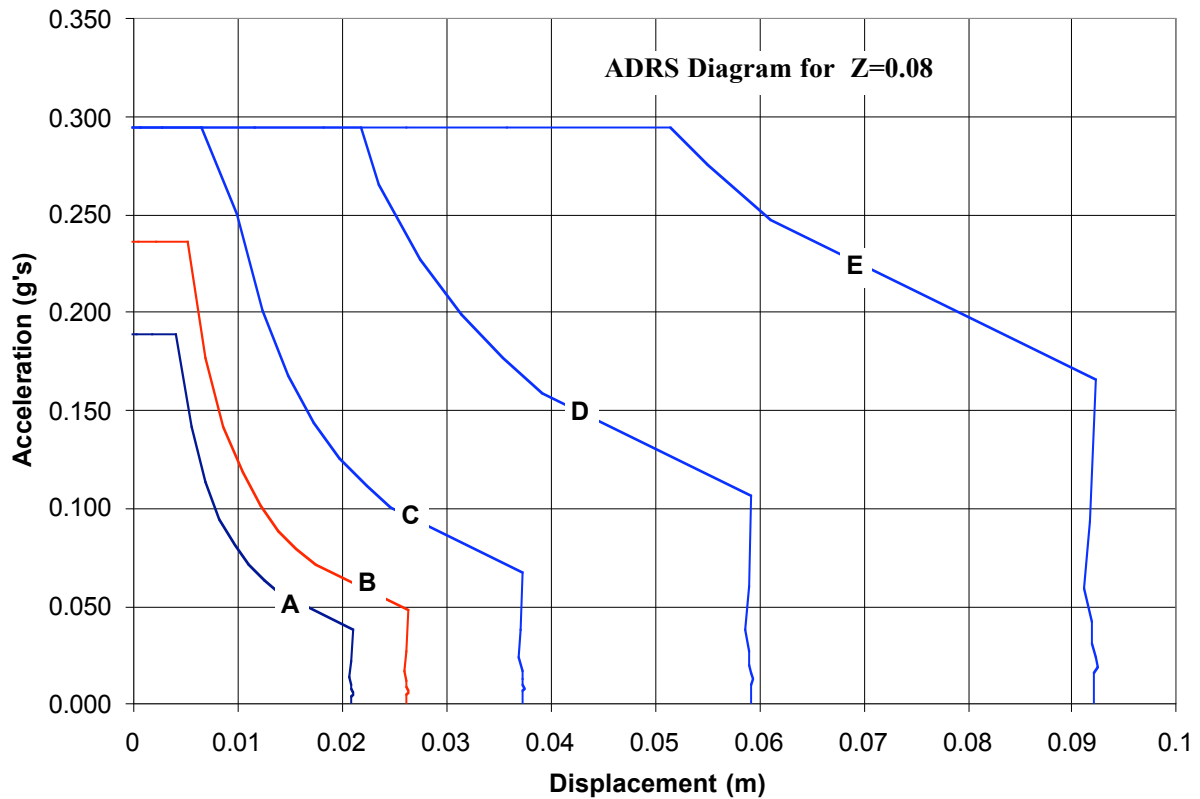


Figure 1: Design response spectra for Z=0.08 plotted in ADRS format

Soil Class	Site factor	Demand Parameters	
		RSV <sub>max</sub>	PDD
A	0.80	85 mm/sec	20 mm
B	1.00	110 mm/sec	25 mm
C	1.40	150 mm/sec	35 mm
D	2.25	245 mm/sec	60 mm
E	3.50	380 mm/sec	90 mm

(a) 500 year return period, Z=0.08g

Soil Class	Site factor	Demand Parameters	
		RSV <sub>max</sub>	PDD
A	0.80	155 mm/sec	35 mm
B	1.00	200 mm/sec	45 mm
C	1.40	270 mm/sec	65 mm
D	2.25	440 mm/sec	110 mm
E	3.50	685 mm/sec	160 mm

(b) 2500 year return period, Z=0.14

Table 2: Velocity and Displacement Demand for Australia (Wilson and Lam 2005)

The stipulated response spectra and the values of PDD, which are based on a “corner period” of 1.5 seconds (Wilson and Lam 2003), are considered reasonable and conservative, although the phenomenon of site resonance phenomenon and magnitude dependence has not been explicitly accounted for in the provisions.

### Displacement based design

Over the past decade, in recognition of the fact that damage is directly related to drift and material strains (as opposed to induced inertia forces), the displacement-based (DB) design approach has been developed (refer review by Priestley 2000). The DB method is



simpler in concept to apply and has great advantages for checking the performance of structures in low to moderate seismic regions at the ultimate limit state (ULS). In such regions, the serviceability earthquake which is associated with a return period in the order of 75 years (50% probability of exceedance in 50 years; abbreviated as 50/50), is typically small and does not need to be considered. In Australia, the ULS earthquake event is typically associated with a return period of between 500 and 2500 years (10/50 – 2/50) and structures should be designed to ensure that collapse is prevented.

The DB method summarised in this paper provides an elegant and simple means of checking performance at the ULS and is considered a major advancement on the more indirect FB method using overstrength and ductility factor (or structural response factor). The DB method requires the structure to be represented as a single degree of freedom structure and the seismic performance is assessed by comparing the displacement demand with the estimated structural displacement capacity. The DB approach, in which demand and capacity are defined in terms of displacement, can be used conveniently to illustrate the importance of magnitude dependence and the phenomenon of soil resonance as highlighted earlier in the paper. A more comprehensive description of the DB method is provided in Wilson and Lam (2005).

The displacement capacity ( $\Delta_c$ ) is obtained from a non-linear push-over analysis where the designer calculates the displacement as a function of increasing horizontal force until the structure is deemed to have failed. In this context, "failure" is assumed to have occurred when the overall structure ceases to be able to support the gravitational loads and collapse follows. There is an important distinction between this definition of failure (in terms of ensuring sustained gravitational load carrying capacity) with the traditional definition of failure used in high seismic regions for ensuring that horizontal resistance capacity is at least 80% of the nominal capacity (NZS1170.5:2004).

The resultant force-displacement plot is commonly known as the "push-over" (or capacity) curve which indicates the capacity of the structure to deform, and can be transformed into an acceleration-displacement curve by normalizing the base shear with respect to the mass of the building. Calculations in developing the transformed capacity curve are material dependent but should include effects such as the elastic and inelastic deflections of the structure together with deflection contributions from foundation flexibility and P-delta effects.

The performance of the building can be simply assessed using a "first tier" approach by comparing the peak displacement demand (PDD) with the displacement capacity ( $\Delta_c$ ). If PDD is less than  $\Delta_c$ , then the structure is deemed satisfactory in terms of its ultimate performance.

If PDD is greater than  $\Delta_c$ , it is recommended that the "second tier" capacity spectrum method (CSM as outlined in ATC40 1996, and Freeman 1998) be used to assess the seismic performance. The transformed capacity curve (as described above) is superimposed onto the demand diagram as shown in Figure 2. If the capacity curve intersects the demand diagram, the structure is deemed satisfactory. The intersection of the capacity and demand curves is defined as the "performance point" and provides a conservative estimate of the actual maximum displacement and acceleration demand on the building. The use of 5% damping is considered as a reasonable representation of real structural behaviour, given that recent research by the authors on the seismic performance of typical Australian structures revealed that effective damping is unlikely to exceed 10% (Edwards 2003).

If an intersection point cannot be obtained, there is a further option for the designer to adopt a refined procedure which involves modifying the demand line for different damping ratios (reflected by the inelastic energy absorptions by the structure). For example, point "2" in Figure 2 indicates that the performance is satisfactory with the updated (higher) damping value. It should be noted that the refinement going from 5% to 10% damping will only decrease the displacement demand by a small amount.

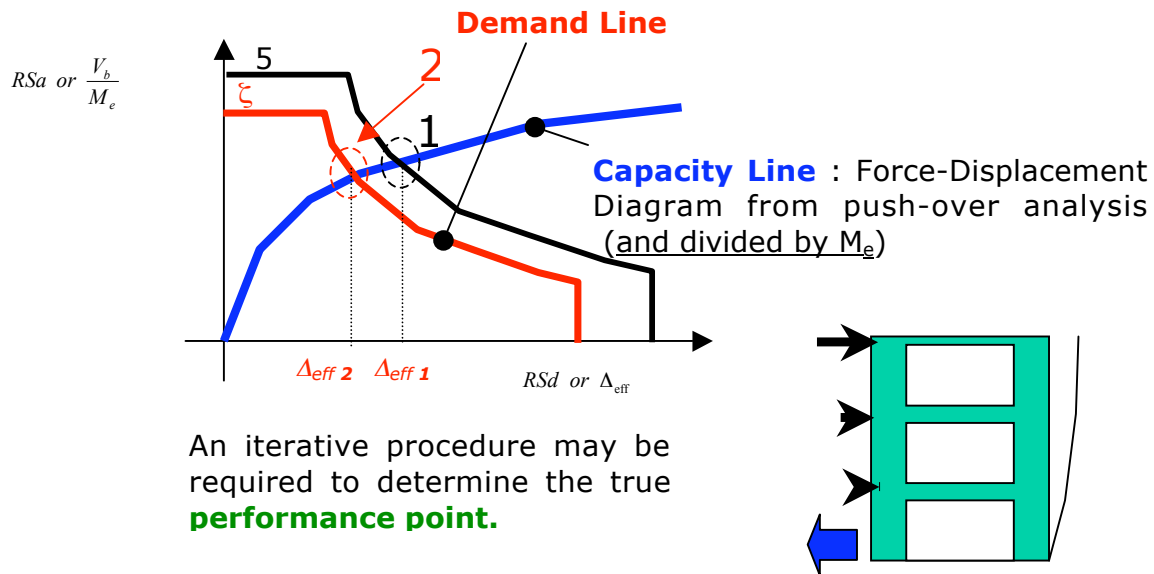


Figure 2: Capacity Spectra with Different Damping Ratios (Wilson and Lam 2005)

This two level Design Based (DB) check of structures has considerable advantages for regions of low to moderate seismicity. The PDD values presented in Table 2 can be converted to estimates of maximum drift demand using the following simplified equations for one storey and multi-storey buildings:

One storey: Max drift =  $PDD / h_1$  (1a)

Multi storey: Max drift =  $[PDD / n \cdot h_1] \cdot PF_1 \cdot \gamma_{max}$  (1b)

Multi storey: Max drift =  $3 [PDD / n \cdot h_1]$  (1c)

where PDD is the Peak displacement demand of SDOF system,  $h_1$  is the storey height,  $n$  is the number of stories,  $PF_1$  is the Participation factor and  $\gamma_{max}$  is the Amplification factor to convert average linear drift to peak drift at any storey. For typical regular structures, the participation factor is around  $PF_1=1.5$  and the amplification factor  $\gamma_{max} = 2$  (Lam 2005) results in a maximum drift demand given by equation (1c).

Equations (1a) and (1c) have been used to estimate the maximum drift demands of 1, 5 and 10 storey regular buildings (assuming a constant storey height of  $h_1=4m$ ) for different soil conditions and return periods of  $RP=500$  and  $RP=2500$  years, as listed in Table 3. The maximum drift demands have been calculated for a zone factor (or acceleration co-efficient of 0.08), corresponding to a 500 year return period event for Melbourne or Sydney. In addition, the value of "n" in Table 3 may be taken to be equal to 1 for the assessment of soft-storey structures where all the drift is assumed to be accumulated in one storey.

Return period	500 yr			2500 yr				
Site Classification	PDD	n=1	n=5	n=10	PDD	n=1	n=5	n=10
	mm	Drift (%)	Drift (%)	Drift (%)	mm	Drift (%)	Drift (%)	Drift (%)
A	20	0.5	0.3	0.2	40	1.0	0.6	0.3
B	25	0.7	0.4	0.2	50	1.2	0.7	0.4
C	35	0.9	0.6	0.3	65	1.7	1.0	0.5
D	60	1.5	0.9	0.4	105	2.7	1.6	0.8
E	90	2.3	1.4	0.7	165	4.1	2.5	1.2

Table 3: Drift Demand Ratios of Regular Multi-Storey Buildings (Wilson and Lam 2005)

The maximum drift demand values presented in Table 3 may be amplified further if the structure is torsionally irregular or reduced if the effects of foundation compliance are significant. The maximum drift demand associated with the 500 year return period event are clearly modest for site classes A, B and C, whilst more demanding for the soft site classes D and E where the PDDs are magnified. Structures considered at most risk in the Australian context with these drift demands are unreinforced masonry, tall buildings with a soft storey configuration, single storey tilt-up construction and some façade systems.

### Future trends

The DB method approach described in Section 8 is deterministic in nature but can be converted to a probabilistic approach for use in risk modeling through the development of representative fragility curves. The intersection of the demand and capacity curve on the capacity spectrum diagram shown in Figure 2 creates a deterministic performance point associated with a level of damage. However, if probabilistic distributions (normal or log-normal) are included in each of these curves to represent the actual variability of capacity and ground motion then the resulting performance can be represented by a log-normal cumulative probability density function, known as a 'fragility curve'. Sample fragility curves developed for damage states of pre-yield, repairable damage, irreparable damage, incipient collapse and collapse are shown in Figure 3.

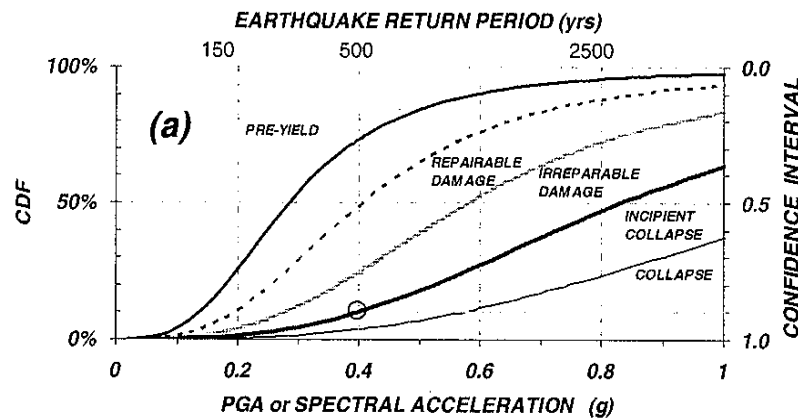


Figure 3: Classical example of fragility curves (after Mander 2004)

The development of representative fragility curves for different structural systems is considered the next challenge in Australian earthquake engineering to assist in risk modelling. Fragility curves can be used to screen code revisions and assess the need for seismic retrofitting. This probabilistic approach has been used in the low-moderate seismic regions of the United States to assist in decision making using a risk-benefit based framework. The method allows a structured framework for assessing public safety and economic losses from damage/failure to public infrastructure and has the potential to assess the effectiveness of various risk mitigation strategies in terms of risk reduction as a proportion of money invested (Ellingwood 2005). The concept of risk is defined in terms of the earthquake hazard, structural vulnerability, consequence of damage and collapse and the context or frame of reference of the risk assessment which varies amongst different stakeholders.

An on-going challenge in Australia is the level of funding invested in earthquake engineering research, which has steadily fallen over the past decade as the memories of the 1989 Newcastle earthquake fade. This is an international challenge for those researchers investigating areas that can be considered low probability/high consequence events and can be demonstrated by the considerable funding that was suddenly made available after the devastating 2004 Boxing Day tsunami that killed some 300,000 people. A study undertaken by Dr Neil Swan for the Geological Survey of Canada (Swan 1999 and reported by Griffith in the AEES newsletter 3/2003) has particular relevance for

Australia. Swan undertook a cost/benefit analysis on the level of funding invested in earthquake engineering research in Canada and concluded that the benefits outweighed the investment by around 10 to 1. A similar study in Australia is needed to demonstrate the importance and benefits derived from a recurrent investment in seismic monitoring, data collection and earthquake engineering research.

### **Summary and concluding remarks**

- Numerous approaches utilizing information developed in the field of seismology, geophysics, geomorphology and neo-tectonics have been applied to Australia for the modelling of its seismic activity, particularly the recurrence behaviour of potential moderate and large magnitude events. The challenge is in reconciling differences between contributions from different modelling approaches and integrating them into a robust model that best reflects the state of the developing knowledge.
- Attenuation relationships have been recommended for different regions within Australia based on different approaches including the Component Attenuation Model (CAM) approach which has now been developed into international applications. Good consistencies between the different approaches have been demonstrated.
- Site classification has been based on identification of the regolith types and site natural period.
- Displacement amplification on flexible soil sites associated with conditions pertaining to soil resonance behaviour has been incorporated into CAM.
- Research into the seismic performances of typical Australian construction which incorporates the use of unreinforced masonry, steel and concrete has been summarised.
- A brief report on current activities with risk modelling and Standards development has been given.
- A displacement based procedure (DB) as an alternative to the traditional force based procedure (FB) has been outlined and is considered a more direct and elegant approach for assessing the seismic performance of structures.
- The future trends in earthquake engineering will be to translate the research outcomes into a probabilistic framework that can be used to provide improved risk-benefit-based design decisions for a range of stakeholders.

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