DEVELOPMENT OF THE NEW AUSTRALIAN EARTHQUAKE LOADING STANDARD

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ABSTRACT

This paper outlines the development of the Australian Earthquake Loading Standard, AS1170.4 published in 2007. Australia is a country of low to moderate seismicity with a number of Magnitude 6.8 events recorded and a moderate 5.6 magnitude event in Newcastle in 1989 that killed 13 people and caused in excess of $2 Billion damage. A new design response spectrum has been developed for Australia which has a very good representation of accelerations, velocities and displacements for rock and soft soil sites. The methodology used to develop the spectrum could be extended to other countries of low to moderate seismicity. The Standard introduces a tiered approach to earthquake loading from a simplistic forced based approach to a more complex displacement based method. The displacement based method has significant advantages in low seismic regions and allows designers to design for gravity and wind loads and then to carry out a displacement check for earthquake effects.

KEYWORDS: Seismic design, Earthquake design standards, Australian seismicity

1 AUSTRALIAN SEISMICITY

The earth’s crust is made up of a number of large tectonic plates that are between 50-100 kilometres thick and each moving in slightly different directions on the molten mantle of the earth as shown in Figure 1. Earthquakes result from a sudden release of strain energy in the tectonic plates that have accumulated from the relative movement of the plates on the earth’s molten mantle. 90% of earthquakes occur on the plate boundaries and are known as interplate earthquakes, whilst the remaining 10% occur away from the plate boundary and are known as intraplate earthquakes. Australia lies within the Indo-Australian plate, which is a thin, significantly fractured shell moving northwards at around 100mm/year. The Indo-Australian plate experiences high compressive stresses caused by the plate colliding with the adjacent tectonic plates north of New Guinea, which is the cause of the intraplate earthquakes experienced in Australia.

The largest earthquake recorded in history is in the order of Magnitude Mn=9.5 with around 1, 10, 100 earthquakes of size Mn=8, 7, 6 expected per annum. In contrast, the largest earthquake recorded in Australia is around 7.2 off the WA coast and 6.9 onshore in WA with a Mn=6 earthquake expected every 5 years and a Mn=5 expected annually. A map showing past seismic events from 1883 in Australia is shown in Figure 2 together with the major faults. Whilst the theory of plate tectonics provides a good basis for understanding the geographical occurrence of interplate earthquakes, it does not provide a basis for predicting the location of intraplate earthquakes. Consequently, Australian seismologists have developed a hazard map for the Australian Earthquake Loading Standard (Figure 3) based on historical seismicity and which is unchanged between the 1993 and 2007 editions of the Standard. The question of whether historical seismicity is the best predictor of future earthquake events is an on-going debate.

Recognition of earthquake hazard in Australia is low amongst the general public, with many events occurring away from population centres and causing little if any damage. There have been exceptions with a 1968 Mn=6.8 earthquake causing significant damage to the township of Meckering, the 1988 Mn=6.8 earthquake near Tennant Creek rupturing the gas pipeline between Alice Springs and Darwin and the moderate 1989 Mn=5.6 Newcastle earthquake (such a magnitude event could be expected every 2-3 years and released only 1/250 the energy of a Mn=7.2 event) killed 13 people, injured 160 people and caused in excess of $2 billion damage. Earthquakes in Australia do occur and can be considered low probability but high consequence events. Most Australian cities are unprepared for earthquakes and the Australian Earthquake Loading Standard can be considered a risk management tool for protecting life whilst accepting damage from an earthquake event. The Australian insurance industry is very aware of the earthquake risk and annually transfers in the order of $200-300 million to re-insurance companies overseas in order to reduce their exposure. The reinsurance companies rate an earthquake in Sydney within their 20 top risk exposures worldwide.

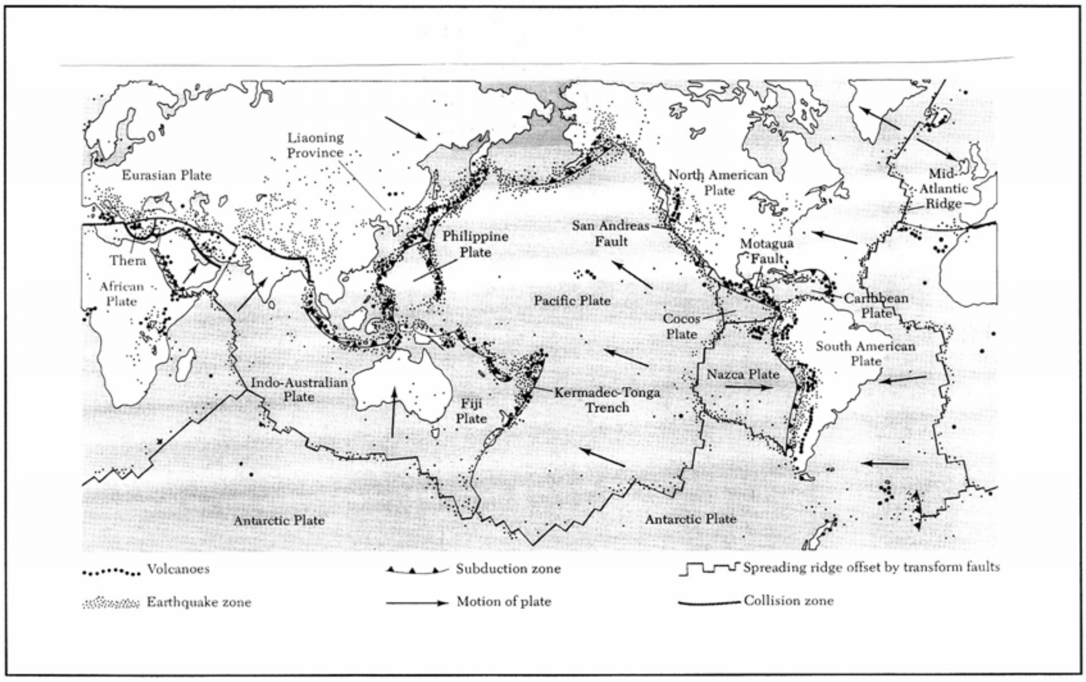

Figure 1 World seismicity and plate tectonics (Bolt 1978)

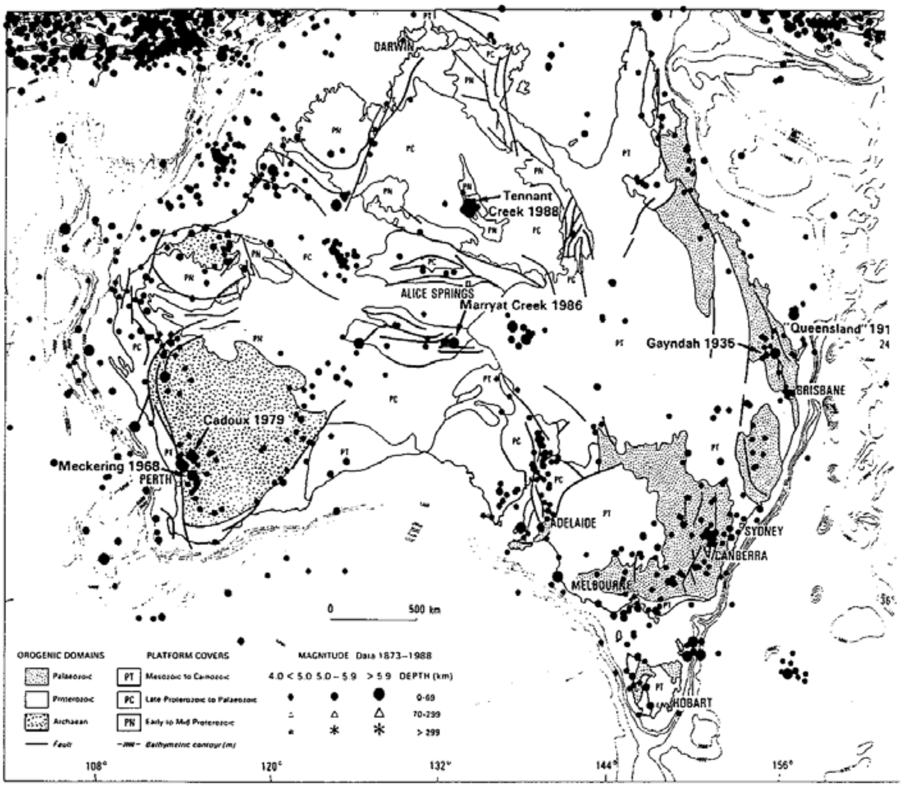

Figure 2 Epicentres of earthquakes in Australia with simplified geological map (AGSO 1995)

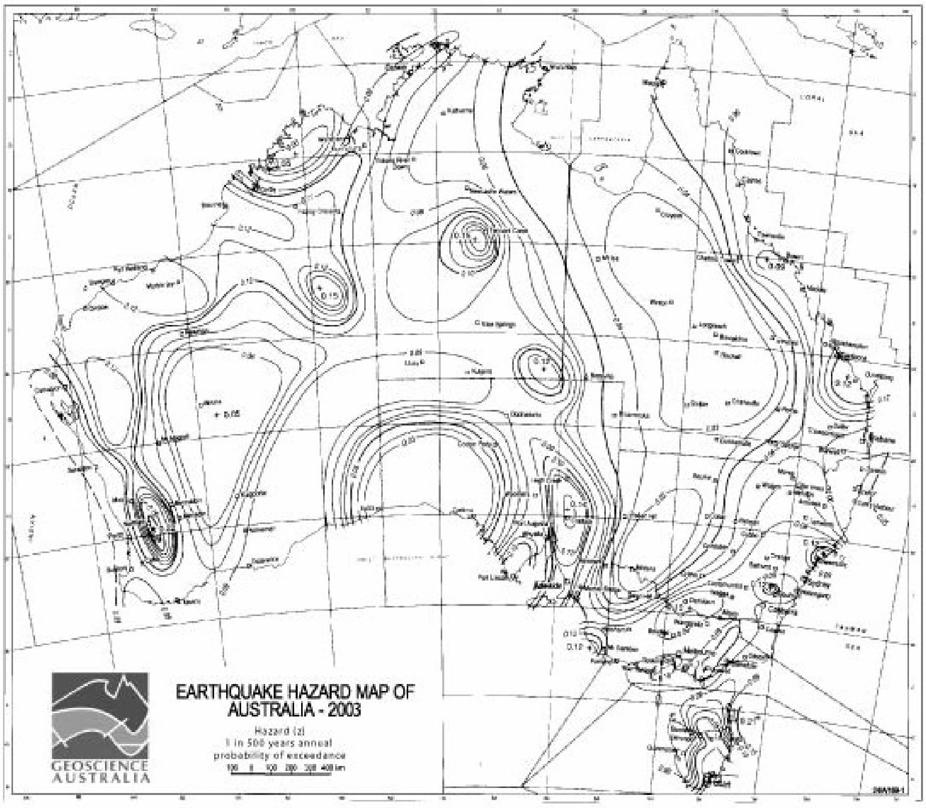

Figure 3 Seismic hazard map of Australia (AS1170.4 -2007)

2 DEVELOPMENT OF AUSTRALIAN EARTHQUAKE DESIGN STANDARDS

2.1 History

Earthquake loading has not traditionally been considered as part of structural design in Australia. In response to the 1968 Meckering earthquake, the Standards Association of Australia issued the ‘Australian Standard for The Design of Earthquake Resistant Buildings AS2121-1979’ (Standards Australia 1979), which introduced earthquake design to a limited number of locations in Australia.

After the 1988 Tennant Creek and 1989 Newcastle earthquakes (which were ironically both in zone 0 of AS2121), Standards Australia reviewed AS2121-1979 and issued AS1170.4-1993 (Standards Australia 1993). Earthquakes were then considered as part of the general loading requirements applicable to all regions of Australia. Subsequent to the issue of AS1170.4-1993, all major material design standards were revised to improve the basic detailing and to include special appendices for earthquake design and detailing. In addition, Standards Australia released AS1170.0 in 2002 which specified minimum lateral forces to improve the robustness of all structures and ensure structures are tied together with defined load paths to transfer lateral loads from the roof to the foundations.

2.2 Development of Current Version

AS1170.4 (2007) was originally to be a joint and harmonised Standard with New Zealand, however severe difficulties developed during the drafting process. The greatest 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 reflected that of a low to moderate seismic country. This was particularly evident in some regions where the seismicity levels were similar (eg. Auckland has a seismicity level similar to Melbourne and Sydney), but the earthquake design practices in each country remains very different. After much deliberation it was decided in 2003 to develop separate Earthquake Loading Standards for each country but to use similar notation where possible.

The 2007 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 design response spectra have been significantly updated with a better estimate of the response acceleration, velocity and importantly displacement for a given location and site and more reflective of a low-moderate seismicity region. The structural response factors (R_f factors) have been standardised and the designer is able to use a non-linear push-over curve to provide a better estimate where required. 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.

Major efforts have been made in assessing the impact of the proposed standard to satisfy Australian Building Control Board (ABCB) regulatory requirements, so that the Standard can be ‘called up’ in the Building Code of Australia (BCA). The conclusions of the impact assessment were that the proposed standard encourages the building industry to provide earthquake protection in a cost-effective manner, and strike a prudent balance between the costs and benefits. The cost is estimated at 0.05% of the total building task.

3 FEATURES OF THE AUSTRALIAN EARTHQUAKE DESIGN STANDARD

3.1 Overview

AS1170.4 (2007) must be read in conjunction with the 'importance level' specified in the BCA, the robustness clauses of AS1170.0 and the detailing clauses of the respective structural material standards. The new standard will require some sort of earthquake analysis for all buildings and utilises a three tiered approach, dependant on the Earthquake Design Category (EDC):

- EDC1 – Simple static analysis (10% weight of the structure)
- EDC2 – Static earthquake analysis
- EDC3 – Dynamic earthquake analysis

Most structures will use the force based principles of EDC1 or EDC2, except tall buildings (where higher mode effects are important) which will use EDC3. The new standard also allows the designer to undertake a displacement based check for earthquake compliance following a design for gravity and wind loads, which is often sufficient in low seismicity areas on rock or firm soil sites. The major impact of the new standard is expected to be low rise structures, particularly of brittle construction, on soft soil sites.

3.2 Determination of Earthquake Design Category

The Earthquake Design Category is evaluated from Table 1 (reproduced from Table 2.6 of AS1170.4 – 2007) and requires the determination of the following parameters:

- Importance Level
- Site sub-soil class
- Hazard Factor (Z)
- Probability Factor (k_p)
- Building Height

Four 'Importance Level' classes are specified in the BCA with the associated return periods (RP) and Probability Factors (k_p) shown in brackets:

- IL1 - very minor and temporary buildings
- IL2 - general buildings occupied by people (RP=500 years, k_p=1.0)
- IL3 - buildings occupied by a large number of people (RP=1000 years, k_p=1.3)
- IL4 - critical buildings with a post-disaster function (RP=1500 years, k_p=1.5)

Five site sub-soil classes consisting of Hard Rock (site class A), Rock (B), Shallow soil (C), Deep Soil (D), Very Soft Soil (E) are described in the Standard.

The Hazard Factor, Z, is equivalent to the effective peak ground acceleration with a return period of 500 years. The Z value in Australia ranges from 0.03 to 0.22 (refer Figure 3) with a Z=0.08 value for Sydney and Melbourne. The Z values are linked to the Peak Ground Velocity (PGV) with Z=0.1g equivalent to PGV=75mm/sec.

Importance level, type of structure (see Clause 2.2)	(k_pZ) for site sub-soil class				Structure height, h_n (m)	Earthquake design category
	E_e or D_e	C_e	B_e	A_e		
1	—				—	Not required to be designed for earthquake actions
Domestic structure (housing)	—				Top of roof ≤8.5	Refer to Appendix A
					Top of roof >8.5	Design as importance level 2
2	≤0.05	≤0.08	≤0.11	≤0.14	≤12 >12, <50 ≥50	I II III
	>0.05 to ≤0.08	>0.08 to ≤0.12	>0.11 to ≤0.17	>0.14 to ≤0.21	<50 ≥50	II III
	>0.08	>0.12	>0.17	>0.21	<25 ≥25	II III
3	≤0.08	≤0.12	≤0.17	≤0.21	<50 ≥50	II III
	>0.08	>0.12	>0.17	>0.21	<25 ≥25	II III
4	—				<12 ≥12	II III

Table 1: Selection of Earthquake Design Categories (AS1170.4 – 2007, Table 2.1)

3.3 Earthquake Design Response Spectra

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 4 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=0.08x1.5=0.12. The site factors listed in Column 2 of the table were inferred from the response spectra stipulated in AS1170.4 (2007). The demand parameter values for the 1500 year R.P. were obtained by multiplying the 500 year

R.P. estimated demand values by a factor of 1.5 as recommended in AS1170.4 (2007).

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 and magnitude dependence have not been explicitly accounted for in the provisions.

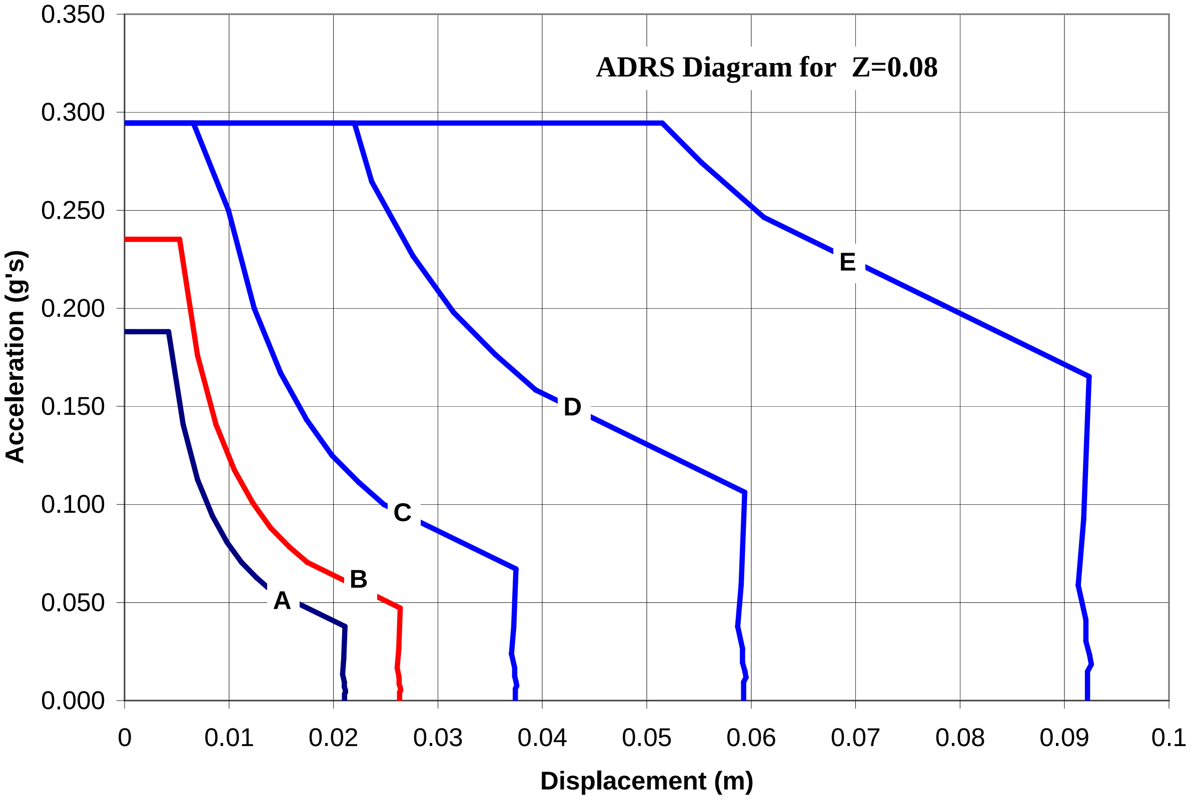

Figure 4: Design response spectra for Z=0.08 plotted in ADRS format

Soil Class	Site factor	Demand Parameters	
		RSV_{max}	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_{max}	PDD
A	0.80	130 mm/sec	30 mm
B	1.00	265 mm/sec	35 mm
C	1.40	225 mm/sec	55 mm
D	2.25	370 mm/sec	90 mm
E	3.50	570 mm/sec	135 mm

(b) 1500 year return period, Z=0.12

Table 2: Velocity and Displacement Demand for Australia (Wilson and Lam 2006)

3.4 Design Approaches

a) Force Based Design

The three standard methods specified for EDC1, EDC2 and EDC3 are all force based methods. The nominal 10% lateral force specified in EDC1 is for short buildings and provides a quick means of assessing compliance. The static and dynamic methods specified in EDC2 and EDC3 use the elastic response spectrum (Figure 4) to define the elastic earthquake response which is then divided by the product of the over-strength factor (Ω) and ductility factor (μ) to approximately account for the inelastic response. The Ω and μ values have been rationalised in AS1170.4 – 2007 with values provided for un-reinforced masonry, limited ductile, moderately ductile and ductile structural systems as summarised in Table 3.

System	**Ductility (μ)**	**Over-strength (Ω)**	**$R_f = \mu \times \Omega$**
Un-reinforced masonry	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 3: Revised ductility and over-strength factors in AS1170.4 (2007)

An alternative method to applying these standard values to allow for inelastic behaviour is to carry out a non-linear push over analysis using the displacement approach outlined in the following section, which is particularly attractive for lower seismicity regions where the displacement demands are more modest.

b) Displacement Based Design

The Displacement Based (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 force-based (FB) method using over-strength 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 (2006).

The displacement capacity (Δ_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 normalising 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 (Δ_c). If PDD is less than Δ_c, then the structure is deemed satisfactory in terms of its ultimate performance.

If PDD is greater than Δ_c, it is recommended that the “second tier” capacity spectrum method (CSM) be used to assess the seismic performance. The transformed capacity curve (as described above) is superimposed onto the demand diagram shown in Figure 4. 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%.

3.5 Summary of Major Changes

A summary of the major changes in AS1170.4 (2007) include:

- Only earthquake loading requirements are retained in AS1170.4-2007, all material detailing requirements have been moved to the corresponding material design standards.
- Section on domestic housing has been rearranged and relocated as a stand alone appendix. All houses in capital cities are no longer required to be designed for earthquake. This will lighten the design task compared with the existing standard.
- Tiered design process that allows designers freedom of choice from basic (force-based) calculation to more sophisticated (deflection-based) design procedures.
- The earthquake spectrum, used to calculate the earthquake loads, has been updated using Australian data reflective of smaller earthquakes. This is an improvement on the 1993 version which was based on the larger Californian interplate earthquake data.
- The format of the new standard is simpler than the existing one.
- Un-reinforced masonry: There are considerable improvements on the treatment of un-reinforced masonry. An appendix to the Australian Masonry Standard AS3700 provides deemed-to satisfy solutions to

facilitate the application of the new AS1170.4-2007. Strict height limits are imposed on load-bearing masonry depending on the seismicity and soil conditions.

4 FUTURE DEVELOPMENTS

The underlying philosophy of the earthquake loading standard is to protect life by preventing building collapse whilst accepting that significant damage could occur (ie. the philosophy is based on life protection rather than property protection).

There is considerable debate internationally regarding the appropriate return period for extreme earthquake events with countries such as Canada and the USA moving from a 500 year (10% chance of exceedance in 50 years 10/50) to 2500 year (2/50) return period for most buildings. The difference between these return periods is much more significant for low to moderate seismic compared with high seismic regions. This means the probability of structural collapse is higher in low-moderate seismic regions compared with high seismic regions when subject to an extreme event larger than the design event. Consequently in countries such as Canada and USA which have both interplate and intraplate seismic regions, the design return period for earthquakes has been lengthened to 2500 years to provide a more uniform risk of collapse across the country. (It should be noted that the increase in wind loads moving from a 500 to 2500 year event is much less significant in comparison with earthquakes in intraplate regions). This trend internationally to increase the return period of the ultimate limit state earthquake event from 500 to 2500 years will be a consideration for Standards Australia and the ABCB.

The next generation of earthquake standards are moving towards performance based designs to not only protect life but also to reduce the significant economic losses resulting from direct damage and business interruption following a severe earthquake. The performance based approaches are framed around client specified return periods for different performance levels:

- Immediate occupancy – negligible damage, operational within one day
- Damage control – moderate damage, operational within 2-3 weeks
- Life safety – possible total property loss
- Collapse prevention – probable total property loss

AS1170.4 (2007) can be considered consistent with the life safety performance level. Other challenges for future developments are to improve the seismic hazard model for Australia and to develop a harmonised earthquake loading standard with NZ.

5 CONCLUDING REMARKS

- Australia is a low-moderate seismic region that is subject to low probability, high consequence earthquake events up to magnitude Mn=7.
- The new earthquake loading standard has a simplified three tiered design procedure that provides freedom of choice for designers from the simple to more complex approaches. The new response spectra has been developed for intraplate regions and allows designers to check earthquake compliance using displacement based methods.

- The impact assessment of the new standard has been estimated at 0.05% of the total building task.
- Future developments for Australian earthquake loading standards include
  - Revision of the hazard map for Australia
  - Review of the ultimate limit state 500-1500 year return period earthquakes, following the international trend of using a 2500 year event to account for the hazard characteristics of low-moderate seismic regions
  - Performance based seismic design approaches that allow clients to specify higher performance levels to be achieved than the minimum collapse prevention limit state.
  - Develop a harmonised earthquake loading standard between Australia and New Zealand
- AS1170.4 addresses the design of new buildings and does not consider existing buildings. Existing buildings considered most vulnerable in the Australian context would be the following types, particularly if torsionally irregular and sited on soft soils:
  - Old un-reinforced masonry cavity brick construction
  - Soft-storey construction
  - Load bearing single storey construction
  - Building façade systems constructed from un-reinforced masonry or glass panels

6 ACKNOWLEDGEMENTS

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