The Chartered Institution of Building Services Engineers (SA Chapter)
Earthquake Design Considerations

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Peter McBean

- 30 years’ experience as a consulting structural engineer
- Joint Managing Director of Wallbridge & Gilbert employing 200+
- Fellow of The Institution of Engineers Australia and Chartered Professional Engineer
- National President of the Australian Earthquake Engineering Society
- Member of Standards Australia Code Committee BD-006-11 responsible for “Earthquake Actions in Australia” (AS1170.4) and BD-002 responsible for “Concrete Structures” (AS3600)
- Active Australian Urban Search And Rescue (USAR) Task Force Engineer, deployed to Christchurch in 2011 to provide structural engineering advice within the Australian USAR response team
- Chair expert panel advising SA Government on seismic retrofit of existing buildings
- Structural Engineering Director for the new $2.3b new Royal Adelaide Hospital
Presentation Overview

• Australian Seismicity, what is the hazard?
• History of earthquake design in Australia
• Earthquake design philosophy
• Lessons from Christchurch
• Non Structural Parts & Components
• Importance Level 4 – Post Disaster facilities
• What is being done?
# Past Earthquakes

## Top 10 Worst Australian Onshore Earthquakes in Modern Times – Ranked by Cost, Magnitude and Damage

*(source Australian Geographic July 10, 2012)*

1. **Newcastle NSW**  
   28 Dec 1989  
   (Magnitude 5.6)  
   Public Holiday

2. **Beachport SA**  
   10 May 1897  
   (Magnitude 6.5)

3. **Meckering WA**  
   14 Oct 1968  
   (Magnitude 6.9)  
   Public Holiday

4. **Ellalong NSW**  
   6 Aug 1994  
   (Magnitude 5.4)

5. **Adelaide SA**  
   1 Mar 1954  
   (Magnitude 5.5)

6. **Warooka SA**  
   19 Sept 1902  
   (Magnitude 6.0)

7. **Meeberrie WA**  
   29 Apr 1941  
   (Magnitude 7.2)

8. **Tennant Creek NT**  
   22 Jan 1988  
   (Magnitude 6.3-6.7)

9. **Kalgoorlie-Boulder WA**  
   20 Apr 2010  
   (Magnitude 5.0)

10. **Cadoux WA**  
    2 June 1979  
    (Magnitude 6.1)
Past Earthquakes

1989 NEWCASTLE NSW (MAGNITUDE 5.6)

- One of Australia’s worst natural disasters
- Killed 13 people, hospitalised 160
- A small intraplate event with soft soils intensifying shaking
- Boxing Day Public Holiday so few people in CBD
- Several events had occurred previously
- Estimated $4 billion of damage to 35,000 homes, 147 schools & 3000 buildings
- Damage over 9,000 square kms with movement up to 800km away

The Newcastle Worker Club - Subsequently demolished & rebuilt. (Photo Courtesy Newcastle Library)

Photo courtesy Cultural Collections, the University of Newcastle, Australia
Past Earthquakes

1968 MECKERING, WA (MAGNITUDE 6.9)

- Epicentre 9km SW of town (130km East of Perth) at 10:59am. Felt over 700km radius
- Length of fault line scarp 37km
- Height of fault line step 1.5m
- Duration 40 seconds
- Most houses and buildings in the district were damaged or completely destroyed
- Cost $1.5 mill equal to $57 mill today
- 20 people injured 50 buildings damaged
- More deaths would have resulted if it hit in the night & again not on a public holiday!
Past Earthquakes

1954 ADELAIDE, SA (MAGNITUDE 5.4)

- Centred at Darlington 12 km south of Adelaide 3.40am.
- Some buildings demolished due to cracking
- 3 serious injuries & damaged 3000 buildings
- Insurers paid approx. three million pounds estimated at $8 mill (about $50 Mill today)
- 30,000 insurance claims but many not insured
- Seismologists and geology experts say no surface rupture was found after the earthquake, which happened at a shallow depth and had one small aftershock.

(Source: SA Govt Records 1954)
Past Earthquakes

1988 TENNANT CREEK, NT (MAGNITUDE 6.3-6.7)

- 3 events greater than magnitude 6 in one day, 30 mins apart
- Warped natural gas pipeline
- Fault line scarp 35km
- Fault line step 2m
- 2 buildings & 3 other structures including hospital damaged
- Thousands of aftershocks with activity still in region

(Source: www.aees.org.au)
Past Earthquakes

2015 FRASER COAST, QUEENSLAND (MAGNITUDE 5.1-5.7)

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Depth (kms)</th>
<th>Lat.</th>
<th>Long.</th>
<th>Magnitude</th>
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<tbody>
<tr>
<td>30/7/2015</td>
<td>9.41</td>
<td>53</td>
<td>25.54S</td>
<td>154.00E</td>
<td>5.3</td>
</tr>
<tr>
<td>1/8/2015</td>
<td>13.38</td>
<td>10</td>
<td>25.38S</td>
<td>154.29E</td>
<td>5.7</td>
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<tr>
<td>1/8/2015</td>
<td>14.46</td>
<td>0</td>
<td>25.39S</td>
<td>154.23E</td>
<td>5.1</td>
</tr>
</tbody>
</table>

- Largest earthquake in region since 1918
- Felt in Brisbane, Gold Coast and Toowoomba

Note: Christchurch earthquake
22 February 2011
Magnitude M6.3

(Image courtesy Geoscience Australia)
Past Earthquakes

THRUST FAULTING PREVALENT IN AUSTRALIA

Types of Faults

Northern Flinders Ranges
Past Earthquakes

EARTHQUAKE FREQUENCY IN AUSTRALIA

• Reality is they are a regular occurrence
• The return periods can be long and they often occur in isolated areas
• On average Australia experiences:
  – 1 shallow earthquake of magnitude 6 or more once every 10 years (equivalent to the 2011 Christchurch earthquake)
  – 1 shallow earthquake of magnitude 5 or more every 2 years (equivalent to those in Newcastle and Adelaide)

Earthquake epicentres in Australia 1841-2000 and recent fault scarps
(Image courtesy Geoscience Australia)
Ratio of 2500 Year Event to 500 Year Event
Design Ground Motion Intensity

For Adelaide, site hazard factor $Z = 0.10g$.

For a 1 in 500 annual probability of exceedance this equates to the following magnitude – distance combinations.

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>70km</td>
</tr>
<tr>
<td>6.5</td>
<td>30km</td>
</tr>
<tr>
<td>6.0</td>
<td>20km</td>
</tr>
<tr>
<td>5.5</td>
<td>10km</td>
</tr>
</tbody>
</table>
Earthquake Design History

1954 - Adelaide Earthquake, M5.4
1968 - Meckering Earthquake, M6.8
1979 - AS2121 Issued
1989 - Newcastle Earthquake, M5.6
1993 - AS1170.4 Issued
2007 - AS1170.4 updated to include post disaster operational requirements.
2008 - BCA Annual probability of exceedance updated

<table>
<thead>
<tr>
<th>Importance level</th>
<th>Building type</th>
<th>Annual probability that the design event will be exceeded*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BCA2007</td>
</tr>
<tr>
<td>1</td>
<td>Buildings or structures presenting a low degree of hazard to life and other property in the case of failure.</td>
<td>1:500</td>
</tr>
<tr>
<td>2</td>
<td>Buildings and structures not included in importance levels 1, 3 or 4.</td>
<td>1:500</td>
</tr>
<tr>
<td>3</td>
<td>Buildings and structures that are designed to contain a large number of people.</td>
<td>1:500</td>
</tr>
<tr>
<td>4</td>
<td>Buildings and structures that are essential to post-disaster recovery or associated with hazardous facilities.</td>
<td>1:800</td>
</tr>
</tbody>
</table>

2009 - Updated version of AS1170.4 adopted by BCA.
Earthquake Design Philosophy

• Significant earthquakes in Australia are rare, but they can and do occur more often than people realise.

• A major earthquake will generate the most severe structural demand experienced by a building.

• Given the rare and extreme nature of earthquakes, for economic reasons, design methods in Standards and Codes focus on preserving life and preventing structural collapse.

• For most buildings, this means that the structural system resisting the earthquake ground motion is permitted to deform inelastically over a number of load cycles.

• Therefore, when current design Codes are used, significant structural and non-structural damage is likely to occur during a moderate earthquake.
Earthquake Design Philosophy

• The inelastic behaviour relies on structural ductility.

• Ductility is an important characteristic of seismic resistant structural systems.

• Ductile materials and connections will **deform but not break** even when subjected to design actions beyond those required by codes and standards. **This behaviour is central to designing robust buildings.**

• In my experience engineers have a poor understanding of the physical significance of ductility.
Ductility is the characteristic of materials such as steel that fail only after considerable deformation has occurred.

Bent metal

DUCTILE

Broken plastic

Nonductile materials (like poorly reinforced concrete) fail without warning in a brittle manner

brittle

NONDUCTILE
Earthquake Design Philosophy

Inelastic response and ductility, $\mu$ using equal-displacement method.

$$\mu = \frac{\Delta_u}{\Delta_{yu}}$$
Earthquake Design Philosophy

![Graph showing elastic and inelastic response spectra](image-url)
Earthquake Design Philosophy
Is designing for earthquakes different to designing for wind?

• For wind, members are proportioned to be stronger than the maximum anticipated demand.

• For earthquake design, we intentionally proportion members to be significantly weaker than would be required to survive the design earthquake elastically and rely on achieving ductile behaviour to accommodate the earthquake demand.
Christchurch Seismic Hazard

22 February 2011 Mn6.3@ 10Km
4 September 2010 Mn7.1@ 40Km

NOTE: Circles and squares correspond to towns and cities.

FIGURE 3.4 HAZARD FACTOR, Z, FOR THE SOUTH ISLAND
Lessons from Christchurch

THE GOOD NEWS

Well proportioned and detailed concrete structures demonstrated that they could survive an earthquake with ground motions more than twice as large as their design event.
Lessons from Christchurch

THE BAD NEWS

There were however many failures of concrete structures, including the tragic complete collapse of two major buildings.
Lessons from Christchurch

THE PYNE GOULD BUILDING

Designed in 1963 before ductile detailing practices were developed. Many Australian buildings are constructed in the same way.
Lessons from Christchurch

THE PYNE GOULD BUILDING

There were many more structural walls at ground floor compared to upper levels. Walls had inadequate longitudinal reinforcement, no confinement.
Lessons from Christchurch

THE PYNE GOULD BUILDING

Shaking in the East – West direction greatly exceeded the capacity of the lightly reinforced core. This was made worse by the vertical discontinuity in the Eastern wall. Column reinforcement poorly confined.
Lessons from Christchurch

BEDFORD ROW CAR PARK

Designed in 1987, prestressed precast concrete double T floor units with 65mm thick topping.
Lessons from Christchurch

BEDFORD ROW CAR PARK

Central precast spine beam supported double - T floor beams with simple dowel connection. Thin diaphragm struggled at connection to ramps and shear walls.
Lessons from Christchurch

BEDFORD ROW CAR PARK

Central precast spine supporting double – T floor beams failed at dowel connection. Whilst not part of the primary lateral load path, the connection was unable to sustain the displacements imposed.
Lessons from Christchurch

LOAD PATHS

- Simple, direct load paths offer predictable behaviour.
- Indirect load paths are problematic
Lessons from Christchurch

LOAD PATHS

Copthorne Hotel, Christchurch
Lessons from Christchurch

LOAD PATHS
Lessons from Christchurch
UNREINFORCED MASONRY STRUCTURES (URM)
Lessons from Christchurch

UNREINFORCED MASONRY STRUCTURES (URM)
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UNREINFORCED MASONRY STRUCTURES (URM)
Lessons from Christchurch

URM BUILDING PERFORMANCE

- Refer Royal Commission of Inquiry report by Jason Ingham and Michael Griffith which studies performance data for 370 buildings
- 97% unstrengthened URM seriously damaged or collapsed (most of these have now been demolished)
- 63% URM in CBD had been strengthened, of those:
  - Parapet, gables, chimneys, out of plane
  - Adhesive anchors didn’t work.

<table>
<thead>
<tr>
<th>% NBS Retrofit</th>
<th>% Seriously damaged or collapsed</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 33%</td>
<td>60%</td>
</tr>
<tr>
<td>34 – 67%</td>
<td>72%</td>
</tr>
<tr>
<td>67 – 100%</td>
<td>24%</td>
</tr>
<tr>
<td>100%</td>
<td>none</td>
</tr>
</tbody>
</table>
Non Structural Parts & Components

RESTRAINT OF SERVICES

Figure 6.4.3.1-6 All-directional cable bracing of suspended piping (Photo courtesy of ISAT).
Non Structural Parts & Components

- Articulation of services crossing seismic joints

Figure 6.4.3.1-1: Pipe joint failure in the 1971, San Fernando Earthquake (FEMA 74, 1994).
Non Structural Parts & Components

- Articulation of services crossing seismic joints

Figure 6.4.3.3-4 Flexible pipe connections at building separation (Photo courtesy of Mason Industries).
Non Structural Parts & Components

- Positional restraint of mechanical plant and equipment
- Shake the table testing of critical items such as back up generators

Figure 6.4.1.1-1  Failed chiller mounts due to insufficient uplift resistance in the 1994 Northridge Earthquake (FEMA 74, 1994).
Non Structural Parts & Components

- Façade drift capacity.
- Full size seismic racking tests undertaken to demonstrate compliance.

Figure 6.3.1.4-5  Broken glass and bent window mullions in flexible building which experienced large inter-story drift in the 1994 Northridge Earthquake (EMA 310, 1998).
Non Structural Parts & Components

- Ceiling system compliance.
- Fire sprinkler detail important.

Figure 2-39:
Ceiling damage in the operating room. The round operating lights on the right were not damaged.
Non Structural Parts & Components

Figure 6.4.7.1-1  Overturned equipment in the 1985 Mexico Earthquake (Photo courtesy of Degenkolb Engineers).
Design of Parts & Components to AS1170.4

• Significantly updated from AS1170.4 (1993)
• 1993 version very conservative and table of components not complete
• Two methods for calculating earthquake actions:
  - Alternative method and higher tier approach based on floor accelerations
  - Traditional equation independent of structure for M&E Engineers

\[
F_p = a_{\text{floor}}[l_c a_c/R_c]W_c
\]

\[
F_p = [k_p Z C_h(0)]a_x[l_c a_c/R_c]W_c
\]
Higher tier approach based on floor accelerations

\[ F_c = a_{\text{floor}}[I_c a_c/R_c]W_c \leq 0.5W_c \]

where

\[ \alpha_{\text{floor}} = \text{effective floor acceleration at the level where the component is situated, calculated from the earthquake actions determined for the structure using Sections 5, 6 and 7 divided by the seismic weight, but not less than } k_pZC_h(0), \]

where the values of \( C_h(0) \) are the bracketed values given in Table 6.1 of AS1170.4.
Design of Parts & Components to AS1170.4

Higher tier approach based on floor accelerations

\[
a_{\text{floor } i} = \frac{F_i}{m_i}
\]

\[
F_i = V_B \frac{m_i h_i^2}{\sum m_i h_i^2}
\]

for \( T > 2.5 \text{sec} \)

\[
F_i = V_B \frac{m_i h_i}{\sum m_i h_i}
\]

for \( T < 0.5 \text{sec} \)
Design of Parts & Components to AS1170.4

Higher tier approach based on floor accelerations

$I_c$ = component importance factor, taken as –

= 1.5 for components critical for life safety, which includes parts and components required to function immediately following an earthquake, those critical to containment of hazardous materials, storage racks in public areas and all parts and components in importance level 4 structures

= 1.0 for all other components

$a_c$ = attachment amplification factor

= 2.5 for flexible spring-type mounting systems for mechanical equipment (unless detailed dynamic analysis is used to justify lower values)

$R_c$ = component ductility factor

= 1.0 for rigid components with non-ductile or brittle materials or connections

= 2.5 for all other components and parts

$W_c$ = weight of the component
Restraint Details

TYPICAL TWO-WAY CABLE BRACING FOR CIRCULAR DUCTWORK
**Restrainment Details**

Unistrut channel P1000
Refer schedule on drawing
SK-D01)

Erico "Strut Seismic Hinge" with 2 x M12
Unistrut nuts to bracing channel at each end

Manufacturer Part Id's:
CSBSH00375EG -- for bolts/anchors M8
CSBSH00500EG -- for bolts/anchors M10, M12
CSBSH00700EG -- for bolts/anchors M16

UNISTRUT CHANNEL BRACE OPTION
Anchoring into Concrete

All anchors in concrete used to transfer structural loads between the concrete structure and connected structural or non-structural parts and components have been:

- pre-qualified for use in cracked concrete and;
- tested as being suitable to resist seismic loads.

Post-Fixed Anchors
Post-fixed anchors, either mechanical or chemical, were required to comply with the either:

- Simulated Seismic Testing requirements of ACI 355.2 (American Code) or;
- European Code (Guideline for European Technical Approval (ETAG) of Metal Anchors for Use In Concrete 001 Annex E).

Cast-in Anchors
Similarly, cast-in anchors were required to be suitable for use in cracked concrete with the capacity of the anchors modified in accordance with the American Code (ACI 318 Appendix D) under seismic load conditions or European Code (Guideline for European Technical Approval (ETAG) of Metal Anchors for Use In Concrete 001 Annex E).
Current Earthquake Design Requirements for NCC Importance Level 4 – (Post Disaster)

AS1170.4 – 2007 requires consideration of two earthquake events:

1. **LIFE SAFETY EARTHQUAKE**
   - Annual Probability of Exceedance 1/1500
   - Low probability / high consequence event.
   - Primary objective collapse prevention and preservation of life.

2. **SERVICEABILITY EARTHQUAKE**
   - Annual Probability of Exceedance 1/500.
   - Higher likelihood of occurrence.
   - Facility is required to remain operational for immediate use after this event.
   - The serviceability performance requirements governed the structural design for the new $2.3b Royal Adelaide Hospital.
Relevance to Client

ASK THESE QUESTIONS:

1) How is business continuity important for the facility?

2) Are valuable / critical assets housed in or near the facility?

If yes, then historical design approaches are unlikely to adequately protect. Even Importance Level 4 structures designed within the last decade are unlikely to remain serviceable after a moderate earthquake.

Expect loss of function for extended periods following an event. Demolition and re-construction likely.
What is being done?

NEW CONSTRUCTION

• Ensure designers and contractors understand the requirement for the facility to remain operational after an earthquake. Most will never have had to comply with these issues.
• Consider “low damage” design strategies.
• Pay particular attention to “non-structural parts and components”

EXISTING CRITICAL INFRASTRUCTURE

• Audit for compliance and risk.
• Prioritise seismic retrofit strategies based on risk (SA Hospitals & NZ vulnerable buildings programs).
• Over time replace assets that are incapable of being economically upgraded.
What is being done?

NEW ROYAL ADELAIDE HOSPITAL OVERVIEW

• $2.3b
• 800 Bed, 2,300 car parks
• 40 technical suites
• 85,000 admissions per year
• 275,000 square metre area
• 100 year design life

• 100,000 cubic metres concrete
• Critical post disaster role
• Designed to remain fully operational following a 1 in 500 year earthquake
• Can operate in “island mode” for 48 hours without external services
Serviceability EQ Design

- A study to establish appropriate drift limits included the following:

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>SUGGESTED DRIFT LIMIT</th>
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<tbody>
<tr>
<td>Eurocode 8</td>
<td>0.5% for brittle non-structural elements.</td>
</tr>
<tr>
<td></td>
<td>0.75% for ductile non-structural elements.</td>
</tr>
<tr>
<td>Priestly et al, 2007</td>
<td>0.5% for masonry infill walls.</td>
</tr>
<tr>
<td>Wilson, 2010 (Expert opinion)</td>
<td>0.5% for brittle non-structural elements.</td>
</tr>
<tr>
<td>Lee, Kato et al, 2006 (quasi-static testing)</td>
<td>0.5% caused insignificant minor damage to dry wall partitions.</td>
</tr>
<tr>
<td>Magliulo et al, 2012 (shake table testing)</td>
<td>Light damage to dry wall partitions up to 0.8%.</td>
</tr>
</tbody>
</table>

- A project serviceability drift limit of 0.5% was adopted. This decision governed the seismic design.
- Reinforced concrete lift / stair cores with additional structural (shear) walls were used to manage the drift.
- Dynamic modelling assumed a cracked but elastic response with $\mu = 1.0$ and $S_p = 0.77$
Summary

- Christchurch sized earthquakes occur in Australia about every 10 years.
- Historical design practices assume buildings will be severely damaged and unserviceable.
- Unreinforced masonry is particularly vulnerable, however many relatively modern structures are also likely to fail.
- New Critical infrastructure can and should be designed to survive earthquakes and remain operational (nRAH). This needs to be explicitly briefed and policed.
- To comply with the NCC, all buildings are required to have services seismically restrained.
Thank You
Any Questions?

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