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RECENT DEVELOPMENTS IN THE RESEARCH AND PRACTICE OF EARTHQUAKE ENGINEERING IN AUSTRALIA

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SUMMARY

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 summarised. Significantly, the developed modelling methodologies for different construction materials including reinforced concrete and unreinforced masonry have been directed towards the displacement-based approach. A brief report on current activities with risk modelling and Standards development is given at the end of the paper.

INTRODUCTION

Over the past 100 years, Australia has been subject to, on average, one earthquake event exceeding Mn 5 every year and one event exceeding Mn 6 every five years (McCue et al, 1995). Most of these earthquake events did not cause casualties but there have 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 Mn 5.6 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

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masonry walls (Melchers, 1990). This was by far the most significant earthquake event in Australian history. Ironically, Newcastle was identified with a zero hazard level in AS2121(1979).

Earthquake engineering research in Australia was limited to seismic activity modelling and seismological monitoring until the mid 1980's when research into the response behaviour of structures in seismic conditions was first undertaken at the University of Melbourne. Even then, 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 Australian Geological Survey Organisation) 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 under the following headings:

(i) Seismic activity modelling
(ii) Attenuation modelling
(iii) Site response modelling and microzonation
(iv) Structural response research
(v) Risk modelling
(vi) Earthquake loading standard

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 (Gaull and Michael-Leiba, 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. 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).

Kernel Method which expresses seismic activity density as a continuous function in space (eg. Woo, 1996) has been applied recently to Australia (Stock and Smith, 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 "bull-eye" effects mentioned previously.

Seismic geomorphology is the branch of science devoted to studying pre-historical earthquake activity based on making observations on 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 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).

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 and Gibson, 2003).

Numerous modelling approaches involving input from a range of disciplines have been described. The challenge is in reconciling differences between the contributions and integrating them into a robust model that best reflects the state of the developing knowledge.

ATTENUATION MODELLING

Intensity attenuation relationships were first developed for different parts of Australia by Gaull and Michael-Leiba (1990) using Iso-seismal maps. Such valuable information on intensity has been translated into peak ground velocity (*PGV*) information using the well known transformation of Newmark and Rosenblueth (1971). The current seismic hazard maps for Australia (in AS1170.4, 1993) is 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.

During the 1990's, 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 *et al*, 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 tri-partite form. However, Somerville's model has not accounted for the variation in the regional geological conditions across the Australian continent as described by Dowrick *et al* (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 *et al* (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 and Lam, 2001; Hutchinson *et al,* 2003; Lam and Wilson, 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 *et al* , 2003; McCue and Sinadinovski, 2003; Wilkie and Gibson, 1995; Gaull and Michael-Leiba, 1990) can be translated into valuable information for response spectrum modelling for the country.

Remarkable consistencies between the Intensity Model of Gaull and Michael-Leiba, the empirical intraplate model of AGSO and CAM have been demonstrated recently (Lam *et al,* 2003). Meanwhile, shortcomings of employing overseas attenuation models (eg. Toro et al, 1997) for applications in different regions within Australia have been highlighted. A response spectrum model recommended for Australia by 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 (Melchers, 1990). Research into site effects can be divided into two main streams, namely (i) site classification and micro-zonation and (ii) soil amplification.

Studies on site classification and micro-zonation was based either on (i) identifying regolith properties and their potential response behaviour using information obtained from seismic cone penetrometer tests (eg. Dhu *et al*, 2002) or (ii) identifying site natural period using borehole information (eg. Lam and Wilson, 1999) or the well known Nakamura technique (eg. Turnbull and Fichera, 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 and Dhu, 2002; Asten *et al,* 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 and Dhu, 2003).

Studies on soil amplification was undertaken as part of the research into the regolith identification procedure described above (Venkatesan *et al,* 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 & Sun, 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. The modelling of such high amplification phenomenon pertaining to resonance conditions has been described in international research literature and has been incorporated into the CAM framework (refer Lam *et al,* 2001; Chandler *et al*, 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 to 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. More recently, the emphasis has been on developing representative non-linear push-over curves for different structural systems for incorporation into the capacity spectrum method (CSM) as recommended in ATC-40 (1996), Freeman, (1998). CSM provides a rapid evaluation technique for assessing the performance of structural systems to extreme earthquake events. Representative earthquake events for Australia can be described in terms of a response spectrum with different return periods using the model outlined in Wilson and Lam (2003).

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 is in progress to evaluate the accuracy and reliability of the analytical model is currently in progress (Rodsin et al 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 *et al* (2003) has developed an innovative new 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 retofitted 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 *et al*, 2001; Abdouka *et al*, 2002). The sub-assemblage 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 debonding 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 to 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.

The behaviour of low rise precast concrete load bearing panel structures was investigated by Robinson et al (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 et al (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 et al 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 *et al,* 2002, Lam *et al,* 2003 and Griffith et al, 2004). 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 complimentary analytical program.

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.

A number of 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 et al, 1998), equivalent damping ratios in reinforced concrete frame buildings for incorporation into the substitute structure method for seismic displacement response predictions (Edwards *et al,* 2003) and the inelastic torsion response of buildings using a displacement based approach (Lumantarna *et al,* 2003).

RISK MODELLING

Geoscience Australia has been undertaking an extensive all hazards risk study for 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 Mn 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 and Jones, 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 is 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 later in 2004. 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 2004 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 factors) have been revised and the designer is able to use a non-linear push-over curve to provide a better estimate where required. The design response spectrum has 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 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.

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. The challenge is in reconciling differences between the contributions 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 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.

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