Liquefaction Hazard Maps for Australia

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SUMMARY:
Screening-level liquefaction hazard maps for Australia are developed corresponding to ground motions for annual probability of exceedance equal to 10% and 2% in 50 years (equivalent to return period of 500 and 2500 years, respectively). The maps integrate the Seed and Idriss (1971) calculation of cyclic stress ratio (CSR) into a GIS-model of ground motions and ground conditions. This study uses earthquake design magnitude from an approximate magnitude deaggregation using the source model characterization developed for the Australian Seismic Hazard Map (AS 1170.4, 2007). Ground accelerations are derived from AS 1170.4 (2007). The liquefaction hazard maps present liquefaction trigger hazard and are intending as screening tool to guide detailed investigation and assessment as required.

Keywords: Australia, liquefaction, hazard, magnitude, deaggregation

1. INTRODUCTION

Liquefaction is a soil behaviour in which saturated soil experiences a reduction in strength due to pore pressure increase during dynamic loading, such as earthquake ground shaking. Consequences of liquefaction include settlement, lateral displacement, loss of bearing capacity, and uplift of buried structures. The historic impact of liquefaction to society is well known from historic earthquakes including billions of dollars in damage from Northridge 1994, Kobe 1995, Loma Prieta (San Francisco) 1989 and most recently Christchurch 2011 and Japan 2011.

Infrastructure planning desk studies in Australia commonly identify liquefaction as a geohazard where susceptible soils exist within the project footprint. Further assessments are required in subsequent feasibility and detailed design phases. Accurately assessing the liquefaction potential is an essential part of geotechnical design considerations.

Although Australia is considered a stable continental region (SCR) and seismic hazard is relatively low compared to other tectonically active areas of the world, geological conditions exist that are susceptible to liquefaction when subject to earthquake ground motion above a minimum value. In fact, liquefaction has been documented in Australia on at least three occasions. In 1897, liquefaction was observed during a large (M_s 6.5) earthquake near Beachport, southeastern South Australia (Collins et al., 2004); in the 1903 Warrnambool, Victoria (M_l 5.3) earthquake (Mitchell and Moore, 2007); and in 1968, numerous ‘sand blows’ were observed following the M_s 6.8 earthquake at Meckering in Western Australia (Collins et al., 2004).

While AS1170.4 (2007) Earthquake Design Actions does not provide guidance for liquefaction triggering assessments, liquefaction assessment methodology has been well established in earthquake engineering practice following Seed and Idriss (1971) and refinement over the last 40 years. These assessments generally need three critical input parameters; design ground motion and earthquake magnitude to estimate CSR, and ground conditions to estimate liquefaction susceptibility and Cyclic

Resistance Ratio (CRR).

In Australian practice, liquefaction triggering assessments start with AS1170.4 (2007) to provide base ground motion levels (Z) from the Australian Seismic Hazard Map and guidance for importance levels to derive desired ground motions for design. Ground conditions are derived from site-specific investigations or, with a lack of site-specific ground investigations, published geologic mapping. For liquefaction triggering assessments in Australia, the critical missing input parameter is the earthquake design magnitude.

In seismically active areas, a typical method for selecting magnitude is to consider the earthquake scenarios that contribute the greatest amount to the ground motion hazard. This is done by examination of the magnitude deaggregation of a probabilistic seismic hazard analysis (PSHA). In Australian practice, AS1170.4 (2007) and Gaull et al. (1990) with revision by McCue et al. (1993) do not provide enough information to readily extract earthquake design magnitudes or to develop magnitude deaggregation plots. As a result, earthquake engineering practitioners in Australia have applied a number of different methodologies to assign earthquake design magnitude for site-specific studies. These methods range from thorough consideration of magnitude to a somewhat arbitrary assignment, and include developing site-specific PSHA deaggregation plots, estimating mean values from regional recurrence curves, using the maximum historic earthquake in Australia for a region, and consideration of a range of magnitudes.

To explore the potential for the liquefaction in Australia, considering the relatively low design ground motions and the arbitrary selection of design magnitudes for Australian liquefaction assessments, an approximate deaggregation magnitude model is integrated into a GIS-based CSR calculation to produce Australia-wide liquefaction triggering hazard maps. The magnitude model estimates earthquake design magnitude by approximating deaggregation plots from information available in AS1170.4 (2007), Gaull et al. (1990) and other recent references.

2. LIQUEFACTION TRIGGERING EVALUATION METHODOLOGY

Seed and Idriss (1971) proposed a simplified procedure for evaluation of liquefaction triggering using standard penetration test (SPT) N-values. Since that time, the simplified procedure has undergone many updates, and procedures using other in-situ test methods, such as the cone penetration test, Becker penetration test, shear wave velocity, and dilatometer have been developed. Each of the evaluation methods compares the soils' resistance to liquefaction with the cyclic stress caused by an earthquake, expressed as the factor of safety against triggering liquefaction, FS_{liq}.

The resistance to liquefaction, commonly termed cyclic resistance ratio (CRR), depends on the relationship between the in-situ density of the soil with its critical state, as well as the behavior of the soil under earthquake-induced cyclic loading. Loose cohesionless soil that is at a state above the critical state line, or loose of critical, is highly susceptible to triggering liquefaction, while plastic soil and soil that is at a state below the critical state, or dense of critical, is least susceptible to triggering liquefaction. Evaluation of susceptibility to triggering liquefaction and CRR is commonly performed using the results of laboratory index testing and in-situ tests, such as those listed above, which have been calibrated with case histories of liquefaction and non-liquefaction to estimate CRR. For this Australia-wide study, the evaluation of in-situ tests is not feasible, so the Australian Site Classification Map is used as a proxy for liquefaction susceptibility and CRR.

The driving cyclic stress cause by an earthquake is commonly termed cyclic stress ratio, CSR. CSR used in the simplified procedure for liquefaction triggering assessment is the average, or equivalent, shear stress induced by the earthquake divided by the in situ effective vertical stress. Seed and Idriss (1971) proposed that the average equivalent CSR for liquefaction triggering assessment is about 0.65 times the peak shear stress, and is estimated as:

$$CSR = 0.65 \cdot \frac{\sigma_v}{\sigma_v'} \cdot A_{max} \cdot r_d$$

Where σ_v is the total vertical stress, σ_v' is the effective vertical stress, Amax is the maximum acceleration (taken as peak ground acceleration, PGA, for liquefaction triggering assessment), and r_d is the nonlinear shear-mass participation factor.

FSliq by definition is the ratio of CRR to CSR, but is also affected by earthquake magnitude, the level of overburden stress, and presence of static shear stress. These aspects are incorporated in a liquefaction triggering assessment using the magnitude-duration weighting factor, DWF, and factors k_σ and k_α to account for overburden stress and static shear stress, respectively.

For this study, liquefaction hazard is mapped in areas where both geologic and seismologic conditions that indicate susceptibility to triggering liquefaction are present. This is achieved by deriving CSR where site Classes D, DE, and E are mapped. The site classes were chosen to represent areas where soil that is potentially susceptible to triggering liquefaction could exist. CSR is computed assuming σ_v, σ_v' and rd are constant near the ground surface, as discussed below, leaving Amax to vary with geographical location. A_{max} is extracted from AS1170.4 (2007) for the appropriate design level. Magnitude duration effects on CSR are including using the DWF, which relies on an earthquake design magnitude. Earthquake magnitude is determined using three separate estimates. Liquefaction hazard is mapped where CSR is above a minimum value, as discussed below. This study assumes that groundwater is at the ground surface.

3. SITE CLASSIFICATION (PROXY FOR LIQUEFACTION SUSCEPTIBILITY AND CRR)

Geologically young or relatively loose soil and uncompacted or poorly compacted fills are generally the materials most susceptible to liquefaction. Among these, loose sands and nonplastic silts are particularly susceptible, but gravels and low plasticity clays can also be at risk. Dense soil and compacted fills have low susceptibility to liquefaction. High plasticity clay and bedrock generally are not susceptible to liquefaction.

Soil that is geologically susceptible to liquefaction commonly exists within deposits of Quaternary-aged sediments and manmade fills. In practice, liquefaction triggering assessments should include evaluation of susceptibility using, at a minimum, gradation and Atterberg limit data (Seed et al., 2003, and Idriss and Boulanger, 2008) prior to estimation of CRR; however for this study, an evaluation of susceptibility is neglected and potentially liquefiable soil is assumed to occur wherever Quaternary-aged sediment or manmade fills are present.

The site classification maps of McPherson and Hall (2007) indicate surficial geology broadly classed by shear wave velocity in the uppermost 30 meters below the ground surface, V_{s30} (Figure 1). As indicated on the maps, the classifications of D, DE, and E correspond generally to Quaternary-aged deposits. Therefore, we have assumed that potentially liquefiable soil exists wherever Site Class D, DE, and E are mapped.

The site classification map was input into the GIS and site classification values for a grid with ~5km spacing across Australia were extracted. The model includes ~160,000 grid cells susceptible to liquefaction from the assigned Site Class D, DE, and E. At the time of this study a digital or detailed version of the site class map was not available; therefore the resolution of this dataset is limited to the maps in the original McPherson and Hall (2007) paper.

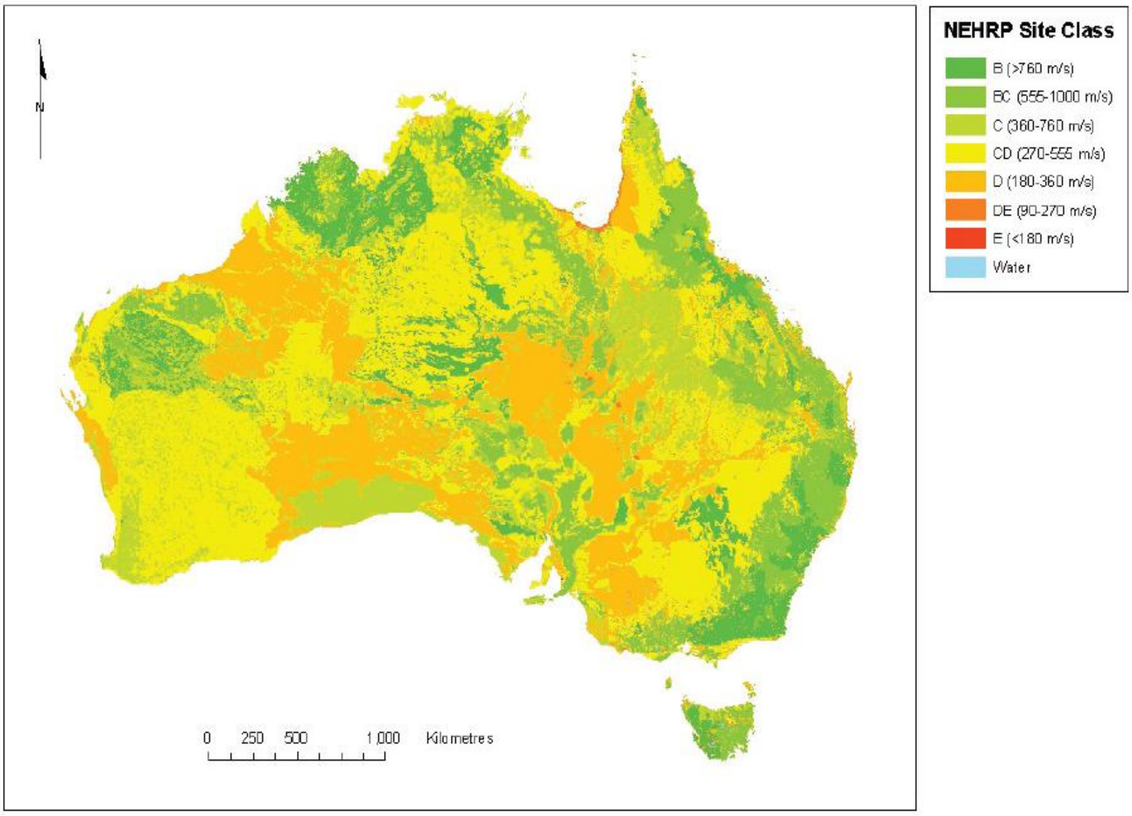


Figure 1. Site Classification Map (McPherson and Hall, 2007)

4. ESTIMATION OF A_{MAX} USING AS1170.4 (CSR)

AS1170.4 provides tools for the engineer to estimate the ground motion for various return periods. The Z-value given in AS1170.4 corresponds to the peak bedrock motion with 10% chance of exceedance in 50 years (return period of about 500 years); the probability factor, k_p, is used to adjust the ground motion for longer return periods; and the spectral shape factor, $C_h(T)$, incorporates local site effects. Peak ground acceleration is determined as the product of Z, k_p, and $C_h(T)$. For this study, Z is taken from AS1170.4, k_p of 1.0 and 1.8, corresponding to annual probability of exceedance equal to 10% and 2% in 50 years (equal to return periods of 500 and 2500 years, respectively) are used, and $C_h(T)$ of 1.1 is assumed.

Ground motions determined using AS1170.4 are a convenient first option, but there are many benefits to using a site specific PSHA. For example, the ability to deaggregate the hazard is vital to understanding the controlling seismological aspects of the hazard, and the use of next generation attenuation relationships (Power et al., 2008) incorporate local site conditions. Inclusion of PSHA into a country-wide liquefaction hazard map is beyond the scope of the preliminary screening maps presented in this paper.

The Australian Hazard Map (AS 1170.4, 2007) (Figure 2) was input into the GIS, georeferenced, digitized, and re-gridded with ~5km spacing across Australia. Estimated Z values were extracted from the map for the ~160,000 grid cells with ground conditions susceptible to liquefaction. The Z values where then scaled for design return period, site class and importance factors.

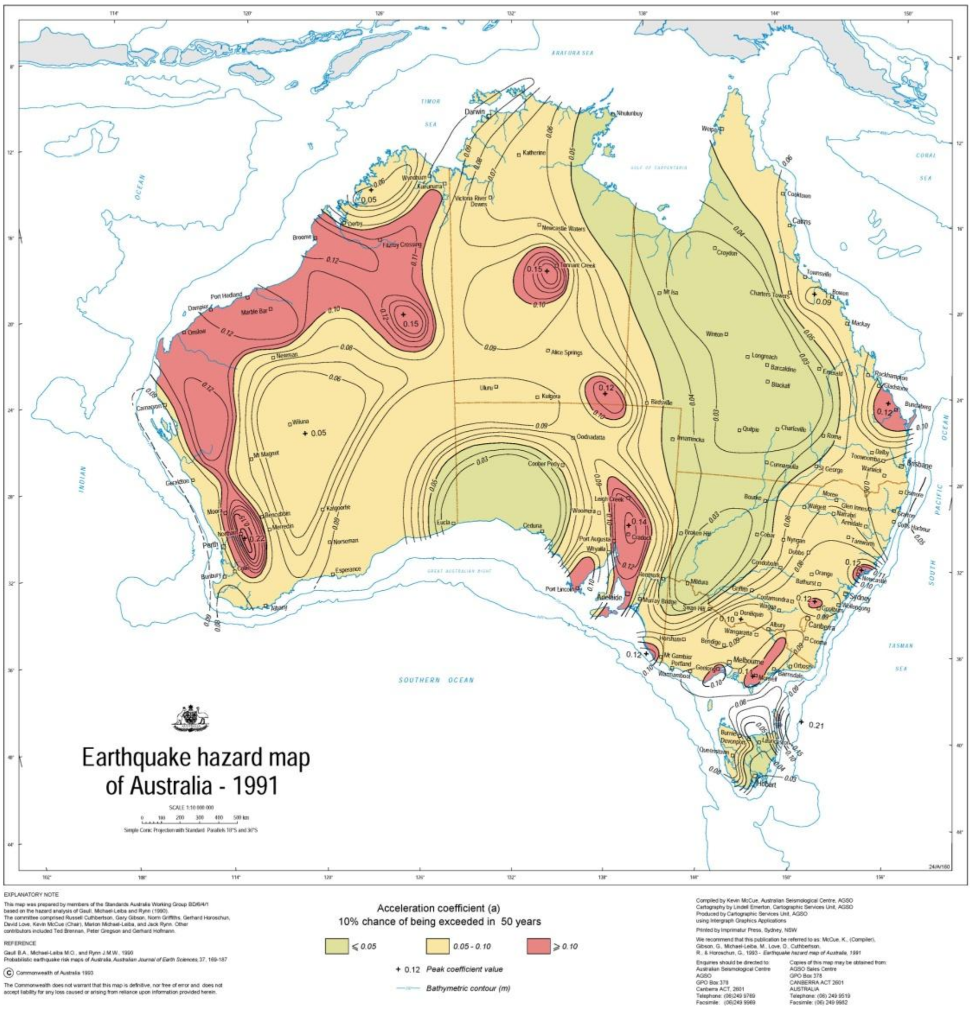


Figure 2. Earthquake Hazard Map (AS 1170.4, 2007)

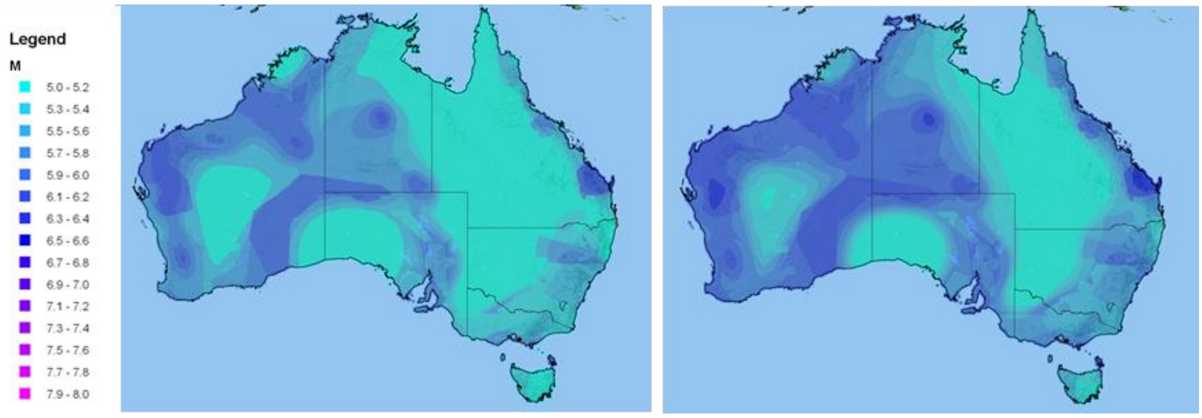
5. ESTIMATION OF DESIGN MAGNITUDE AND THE DURATION WEIGHTING FUNCTION (DWF)

The impact of duration of strong ground motion on CSR is considered using the magnitude-duration weight factor, DWF. For this study k_σ and k_α are attributed to cyclic resistance and do not impact the determination of CSR. Design-level assessment of FS_{liq} should incorporate all of these factors, however.

The magnitude-duration weighted cyclic stress ratio, $CSR_{7.5}$, is computed as:

$$CSR_{7.5} = \frac{CSR}{DWF}$$

DWF requires a design magnitude as input, which is determined using the Approximate Deaggregation Method for Determination of Design Earthquake Magnitudes for Australia presented by Dismuke and Mote (2012) presented concurrently at this conference (Figure 3).



(a) (b)

Figure 3. Design Magnitude for annual probability of exceedance equal to (a) 10% in 50-years and (b) 2% in 50-years (corresponding to (a) 500 and (b) 2,500-year return period ground motions)

Currently, there are four relationships for DWF that are commonly used for computation of CSR. Youd et al. (2001) was the standard reference for liquefaction triggering assessment for many years and continues to be used in some parts of the world; however, recent updates to liquefaction triggering, including an expanded database of case histories, have been issued by Cetin et al. (2004), Moss et al. (2006), and Idriss and Boulanger (2008). For this study we are only considering DWF relationships of Moss et al. (2006) and Idriss and Boulanger (2008). The Youd et al. (2001) DWF relationship was not used because it has been superseded by the updated triggering procedures, and the relationship of Cetin et al. (2004) was not used because it was essentially superseded by Moss et al. (2006). DWF was capped at values corresponding to M5.25 for the Idriss and Boulanger (2008) relationship and at M5.5 for Moss et al. (2006) based on the range of values presented in each reference. Regardless, future design level triggering evaluations should use the DWF interpretation appropriate for the specific method.

6. DETERMINATION OF CSR$_{7.5}$

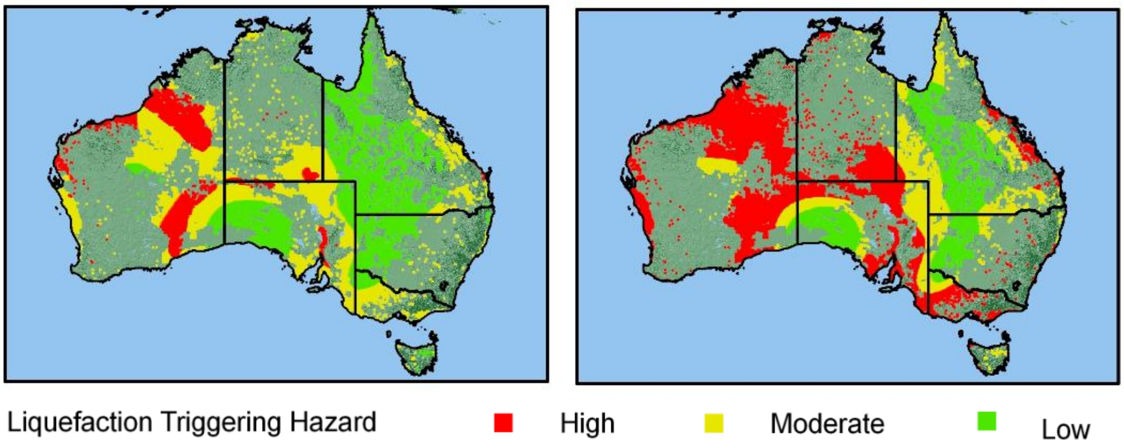
CSR$_{7.5}$ was calculated considering the three magnitude models for ~160,000 - 5km grid cells across Australia under the following assumptions:

- A_{max} is equal to Z (AS1170.4-2007) with site factor of 1.1 for Site Class D, DE, and E and importance factors corresponding to return periods of 500 and 2500 years;
- The ratio of σ_v to σ_v’ is about 2 for an assumed total unit weight of 20 kN/m^3;
- Groundwater level is at or near the ground surface;
- r_d is 1 near the ground surface; and
- An average DWF of capped values determined by Moss et al. (2006) and Idriss and Boulanger (2008).

7. SCREENING LEVEL LIQUEFACTION HAZARD MAPS

Liquefaction hazard maps are presented in Figure 4 for annual probability of exceedance equal to 10% and 2% in 50 years (equivalent to return periods of 500 and 2500 years, respectively). On the maps, red is considered high liquefaction triggering potential, orange is moderate, and green is low triggering potential. The gray zones are identified as rock (Site Class S, B, or C).

Liquefaction and no-liquefaction case history databases recently used by Cetin et al. (2004), Moss et al. (2006), and Idriss and Boulanger (2008) for SPT- and CPT-based triggering assessment procedures indicate that the minimum CSR7.5 where liquefaction was observed is about 0.05 for very loose to loose sand and about 0.1 for loose to medium dense sand. Thus, liquefaction hazard is considered to be high where CSR7.5 is greater than 0.1 (red areas on the hazard maps) and moderate where CSR7.5 is greater than 0.05 but less than 0.1 (yellow areas on the hazard maps).



(a) (b)

Figure 3. Screening-level liquefaction hazard maps for annual probability of exceedance equal to (a) 10% in 50-years and (b) 2% in 50-years (corresponding to (a) 500 and (b) 2,500-year return period ground motions)

8. CONCLUSIONS AND DISCUSSION

Although soil susceptible to liquefaction exists in geologically-young sediments throughout Australia, liquefaction potential is limited by seismological aspects, such as ground motions levels and earthquake magnitude. The basis of the liquefaction hazard maps developed in this study, is the determination of earthquake induced cyclic stress that is sufficient to trigger liquefaction. In the absence of a deaggregated PSHA, controlling magnitudes and magnitude-duration weighting factors are determined using several simplifications of the PSHA underlying the potential ground motions. The liquefaction hazard maps are intended as an aid for planning site investigations, not as an assessment of liquefaction triggering at a specific site.

The liquefaction hazard maps (Figure 4) are developed for Australia corresponding to AS1170.4 design level ground motions for annual probability of exceedance equal to 10% and 2% in 50 years (equal to return periods of 500 and 2500 years, respectively) provide screening level tools to assess liquefaction triggering hazard throughout Australia. The maps assume groundwater is at the ground surface and use the small scale Australian Site Classification map as a proxy for ground conditions, therefore consideration of groundwater and confirmation that local Site Class falls into D, DE and E is required to properly apply these maps.

In practice, if ground conditions at a site are Class D, DE, or E and fall into the high liquefaction hazard zone of the design return period ground motion, a site investigation should include components specifically for assessment of susceptibility and triggering of liquefaction. For example, sieve analyses and Atterberg limits determinations to assess susceptibility and cone penetration tests paired with borings to define stratigraphy and assess triggering potential. If a site falls in the moderate zone then confirmation of soil conditions is suggested before a further detailed liquefaction assessment is implemented. For all hazard levels, site specific knowledge of soil and groundwater conditions should be used to plan site investigations, in cooperation with these maps.

A typical method for selecting magnitude is to consider the earthquake scenarios that contribute the greatest amount to the ground motion hazard through an examination of the magnitude deaggregation of a PSHA. In Australia, this information is not readily available in AS1170.4 (2007) however; the Australian Hazard Model provides information on the broad seismic sources quantified into areal source areas, making it possible to estimate the relative contribution of magnitude to the hazard by making a few assumptions. The earthquake design magnitude selection model used in this study approximates the magnitude deaggregation and, the authors feel, provides a basis to guide earthquake design magnitude selection for liquefaction assessment.

The methods presented in this paper are simplifications of the seismological aspects of the ground motion hazard, and should be considered preliminary until such time as deaggregated results of a PSHA are incorporated. The scale of the mapping is considered on the order of 1:10,000,000 due to the digitization of a number of small scale figures.

Development of these maps includes several assumptions that tend to be conservative, such as:

- Soil that is susceptible to triggering liquefaction is assumed to be present everywhere Site Classes D, DE, or E is mapped. Although this is a conservative assumption, as it yields the greatest area of positive liquefaction hazard, it is necessary to ensure that site investigations are designed to gather the proper data for assessment of liquefaction.
- The ground motion variability of one standard error that is assumed in the approximate deaggregation model yield design magnitudes that are likely larger than design magnitudes determined by considering more than one standard error, as is customary in modern PSHA.
- DWF values are capped at M 5.25 to 5.5. This was done because the DWF relationships are not developed for lower magnitudes. Although it is unlikely that earthquake-induced liquefaction is triggered by earthquakes with low magnitudes, the capping of DWF adds to conservatism in the hazard results.
- Calculation of CSR at the ground surface with a high groundwater table yields maximum CSR values. Actual site and groundwater conditions will likely yield lower CSR. This aspect of the hazard maps was implemented for simplification. The hazard maps should always be reality checked against local site and groundwater conditions.

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