Site classification for earthquake hazard and risk assessment in Australia

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Abstract

One of the more important observations from the 1989 Newcastle earthquake was the spatial distribution of earthquake damage, which was strongly related to variability in near-surface regolith properties and their influence on ground-shaking (i.e. site response). This association between ground shaking and sediment distribution is well recognised, but has not previously been investigated for much of Australia.

In an effort to characterise the Australian regolith in terms of its ability to modify earthquake energy, Geoscience Australia, in collaboration with Risk Management Solutions Inc., has developed a national site classification map of Australia for application in broad scale earthquake hazard and risk assessment. Site classes are assigned according to the California-derived classification of Wills et al. (2000), which uses the relationship between geological materials and the shear wave velocity of the upper 30 m (V_s^{30}). Adjustments to the classification scheme are suggested to better account for the occurrence of weathered regolith in bedrock dominated areas. The application of this classification is successfully tested in Australia using borehole data from a variety of Quaternary environments in the Newcastle, Sydney and Perth urban areas.

Introduction

The properties of the regolith material beneath a site can significantly influence the amplitude, frequency and duration of earthquake ground motions, and thereby affect the occurrence and degree of damage to buildings and other structures (Seed & Idriss, 1969; Idriss, 1990). This was demonstrated by the strong spatial correlation between building damage and site conditions observed in the 1989 Newcastle earthquake (Chandler et al., 1991). Previous national scale hazard map products for Australia have not accounted for site effects, and so may significantly underestimate ground motion. As a result, the development and incorporation of a national site classification model and associated amplification factors is essential for the rigorous assessment of earthquake risk in Australia.

This study discusses the development of a broad scale site classification map representing the relative potential response of all major occurrences of surficial geological materials across Australia to earthquake ground shaking. The map has been developed using a number of national and regional scale geological and geotechnical datasets, combined with more detailed local data where available. The site classification scheme applied is that developed by Wills et al. (2000) for California, with modifications made to account for Australian conditions. Amplification factors being developed in association with the site classification map will not be dealt with in this paper.

The map and underlying methodology are validated for Quaternary deposits in the Perth, Sydney and Newcastle urban areas using either measured or calculated shear wave velocity data from previous geotechnical investigations. This analysis demonstrates the influence of grain size and unit age on site classification, as well as the importance of capturing sediment thickness information. It also illustrates the limitations of this type of broad scale investigation, reinforcing the need to collect higher resolution geophysical and geotechnical data when conducting local or site-specific earthquake risk assessments.

Site classification

Local site conditions can significantly alter the amplitude and frequency content of earthquake ground motion, where the regolith material physical properties, such as shear wave velocity (V_s), particle size, density and plasticity, exert a major control on the degree of amplification or attenuation experienced by travelling waves. Three important characteristics of the subsurface material which influence ground motion are impedance, absorption and basin geometry.

A site class represents a group of geological materials that are considered likely to exhibit a similar physical response to a given earthquake ground motion. They are defined by relationships between the physical properties of the regolith materials (such as thickness and particle size) and known responses to ground shaking of materials with similar properties. Correct site class definition is therefore essential for determining the potential response of structures.

As is often the case in broad scale site characterisation, a lack of relevant data makes it almost impossible to assign site classes based on all of the properties influencing site response, including basin geometry. A simpler approach is to consider the ground motion amplification affect of impedance alone (Borcherdt, 1994). In this case, the preferred method for defining site classes is on the basis of the shear wave velocity of the top 30 m below the ground surface (V_s^{30}). This method has become widely accepted as the standard way to characterise site conditions for earthquake site response assessment (Anderson et al., 1996; Wills & Silva, 1998; Wills et al., 2000; Boore, 2004; Choi & Stewart, 2005; Holzer et al., 2005).

Although V_s^{30} is best determined by direct measurement, such data is often not available. As a result, it is necessary to establish a proxy for this parameter. The use of geology as a surrogate for shear wave velocity forms the basis for determining the influence of site conditions in many seismic hazard assessments, and has been tested by numerous workers characterising strong motion sites in the USA, particularly in California (e.g. Fumal & Tinsley, 1985; Park & Elrick, 1998; Wills et al., 2000; Wills & Clahan, 2006).

Site classification in Australia

In Australia our understanding of the relationship between regolith materials and their response to earthquake ground shaking is very poor. This is due to both a paucity of ground motion data and a lack of available geotechnical and geophysical data that could be used to define typical V_s^{30} ranges for different near-surface regolith materials. Accordingly, the site classification we apply in this study is that defined by Wills et al. (2000). This is a version of the National Earthquake Hazard Reduction Program (NEHRP) site classification scheme (Building Seismic Safety Council, 2004) modified to account for the variation in measured V_s^{30} for geological units in California.

Significant areas of the Australian continent are composed of very old bedrock units exhibiting substantial weathering (Chan et al., 1986). The presence of these weathered materials can have a major impact on earthquake site response (Davis, 1995; Steidl et al., 1996), as average acceleration response spectra on weathered rock sites may be up to 20% higher than those at competent rock sites (Idriss & Silva in Rodriguez-Marek et al., 2001).

Table 1. Modified NEHRP site classes, associated V_s^{30} values and general groupings of geologic units associated with each class, based on 556 measured profiles from California (Wills et al 2000).

Site Class	V_s^{30} (m/s)	Geological Materials
B	> 760	Plutonic/metamorphic rocks incl. most volcanics; pre-Tertiary sedimentary units
BC	555 - 1000	Cretaceous fine-grained sediments; serpentine; sheared/weathered crystalline rocks
C	360 - 760	Oligocene – Cretaceous sedimentary rocks; coarse-grained

		younger material
CD	270 - 555	Miocene fine-grained sediments; Plio-Pleistocene alluvium; coarse younger alluvium
D	180 - 360	Holocene alluvium
DE	90 - 270	Fine-grained alluvial/estuarine deposits
E	< 180	Inter-tidal mud

The classification of Wills et al. (2000) does little to account for variations in rock weathering, and therefore an adjustment to the site class definitions is necessary when applying this scheme to weathered bedrock in Australia. A generalised relationship is developed between a recommended rock weathering classification for Australia (Eggleton, 2001) and site class, by relating the typical properties of a material in a given weathering state with available data on Vs and regolith thickness (McPherson and Hall, in prep). An average V_s^{30} estimate and associated site class are assigned to each weathering state based on the limited published information available for Australia (e.g. Awad & Peck, 1976; Herbert, 1979; Henderson, 1981; Hofto, 1990; McNally, 1993; Anand & Paine, 2002; Dhu & Jones, 2002; Nott, 2003; Willey, 2003). Moderately weathered to fresh bedrock is assigned to site class B, highly weathered bedrock is defined as site class BC, and extremely weathered bedrock, with or without residual soil, is typically assigned to site class C.

The relationships between regolith properties and site classes defined for Australia can now be applied on a national scale. The resulting regolith site classification map is shown in Figure 1.

Site class validation

The site classification map and the underlying methodology are validated using a variety of geophysical and geotechnical datasets from the Perth, Sydney and Newcastle urban areas. To test the variation in typical regolith behavior with unit age and texture, composite velocity profiles and associated V_s^{30} statistics (Table 2) are calculated for selected regolith material types in each region.

The Perth metropolitan region is underlain by Pleistocene sands and silts to depths of up to 100 m (McPherson & Jones, 2005). Shear wave velocities measured at 57 SCPT sites around the urban area show a clear correlation between V_s^{30}, sediment texture and age. Medium- to coarse-grained Pleistocene sands and silts have a median V_s^{30} of 302 m/s (class CD-D), while fine- to medium-grained materials of a similar age show consistently slower site conditions, with a median V_s^{30} of 253 m/s (class D-DE). A similar trend is observed in Holocene aged sediments, with sands having a median V_s^{30} of 287 m/s (class CD-D), and fine grained silts and clays a median value of 230 m/s (class D-DE).

Botany Bay contains some of the largest accumulations of Quaternary sands and silts in the Sydney region (Haworth, 2003). No directly measured shear wave velocities are available in this area, however calculated shear wave velocities from SPT blow counts, quantify the variation in shear wave velocity and basement depths for over 300 locations across the basin. Where Quaternary sediment thicknesses exceed 30 m calculated median V_s^{30}ranges from 200-250 m/s, equivalent to site classes D or DE. The underlying Hawkesbury Sandstone has V_s^{30} values in the range of 1200-2500 m/s (class B) depending on the degree and thickness of weathering. Where depth to basement is less than 30 m, V_s^{30} values increase and site classes change accordingly. This illustrates the importance of regolith thickness in determining site class assignments, as observed by Wills & Clahan (2006).

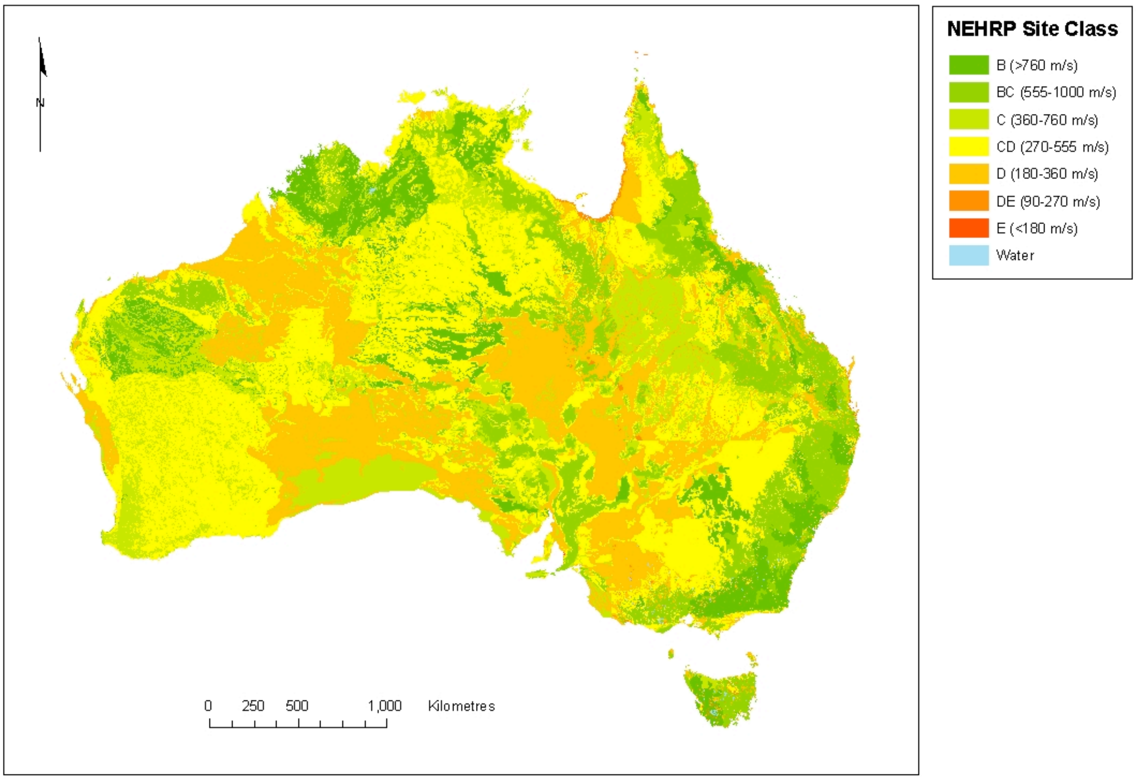

Figure 1. Site classification map of Australia. Over 40 geospatial datasets are incorporated into the site conditions dataset to provide complete country-wide coverage. Input resolution varies depending on population, with all major cities covered by 1:100,000 (or higher) resolution maps.

Table 2. Calculated V_s^{30}statistics for selected rock units in Perth, Sydney and Newcastle regions, where sediment depths > 30 m. V_s^{30}lower and V_s^{30}upper represent 95% and 5% uncertainty bounds.

Region	Age	Material Type	V_s^{30}median	V_s^{30}lower	V_s^{30}upper	No. of Sites
Perth	Holocene	Silts/ clays	230	155	262	5
	Holocene	Mixed sand	287	236	262	4
	Pleistocene	Fine to medium sand	253	215	303	16
	Pleistocene	Medium to course sand	302	228	379	13
Sydney	Holocene	Fill/ peat	269	255	565	7
	Holocene	Fine/ medium sand	284	256	461	214
	Holocene	Course sand	312	194	485	5
Newcastle	Holocene	Silts/ fine sand	200	160	227	6
	Holocene	Fine to medium sand	262	214	336	9

The central Newcastle area is dominated by Holocene fluvial and estuarine sediments associated with the Hunter River. Where sediment thickness exceeds 30 m, median V_s^{30}values decrease from 262 m/s to 200 m/s (effectively transitioning from class D to class DE) as the alluvium thickens and texture becomes finer in proximity to the Hunter River. However, the presence of shallow bedrock (depth to basement < 30 m) causes the V_s^{30}values to increase significantly at sites around the edge of the alluvial deposits.

The measured relationships between regolith properties and Vs30 for selected sites in Australia (Table 2) are consistently grouped by the modified scheme of Wills et al. (2000), demonstrating the suitability of this method for undertaking regional scale site classification in Australia. However, the variability in regolith material type and local basin conditions highlight the difficulty in classifying for site response at higher spatial resolutions, and reinforce the importance of acquiring detailed, directly measured data for local and site-specific studies.

Conclusions

The site classification map presented here is appropriate for application in national to regional scale earthquake hazard and risk assessment in Australia, in conjunction with appropriate amplification factors. Calibration with geotechnical, geophysical and borehole geological data for Quaternary environments indicates that average site conditions are adequately represented at this scale, although local variability in regolith properties means that this product is inappropriate for site-specific assessment. This study suggests that the site classification methodology of Wills et al. (2000) can be successfully applied to other tectonic settings, with modifications to account for bedrock weathering. However, care must be taken to account for sediment thickness, as excluding such information may lead to the misclassification of regolith properties, particularly with respect to their earthquake ground shaking potential (Wills & Clahan, 2006).

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