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Liquefaction Triggering Sensitivity to Seismic Inputs in Low Seismicity Regions and Resilient Geotechnical Design Implications

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ABSTRACT

The resilience of a community can be directly related to the performance of its infrastructure. Current seismic design practice is starting to look beyond code to resilience and the consequence of liquefaction risk on the recovery of the greater community. In low seismicity regions, liquefaction triggering is marginal at design hazard levels. This paper shows that liquefaction triggering assessments in low seismicity regions are particularly sensitive to design event magnitudes. The lack of guidance and the large epistemic uncertainty in seismic hazard for low seismicity regions make the selection of a magnitude for a corresponding design level open for interpretation. Problems with the traditional approach of applying the magnitude-distance deaggregation to derive design magnitude in these regions is highlighted. Currently a resilient seismic design approach has not been codified, but guidelines and legislation are starting to come into place which require owners/operators of critical infrastructure to comply with mandatory obligations based on a resilience framework. Ultimately it is up to the geoseismic practitioner to understand liquefaction trigger risk and a resilient approach should be considered where consequence to the greater community is evaluated and performance based design allows critical or lifeline infrastructure to get a community back up and running.

Introduction

Lessons learned from recent earthquakes show that the resilience of a community can be directly related to the performance of its lifeline infrastructure. With transport, power, communications, and water functional, communities are able to respond and recover quickly while minimizing both economic loss and long-term population decline. Current seismic design practice is starting to look beyond code to resilience and the consequence of liquefaction risk on the recovery of the greater community (Almufti 2013). Recent study on resilient seismic design for the city of Los Angeles made specific recommendations to make water and communication infrastructure resilient and more robust to a major damaging earthquake (Los Angeles, 2014). When considering the geotechnical resilience of infrastructure during earthquakes, understanding risk and uncertainty in liquefaction design is important.

Liquefaction is a soil behavior in which a saturated soil deposit experiences a reduction in strength due to a rise in pore water pressure in response to rapid loading, such as earthquake ground shaking. Observed consequences of liquefaction include level ground settlements, lateral displacements towards rivers (lateral spreading), loss of bearing capacity (punching shear, SSI ratcheting, differential settlement), and uplift of buried structures (sewers, tanks). The historic impact of liquefaction to society is well known from historic earthquakes including billions of

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dollars in damage from 1994 Northridge (California), 1995 Kobe (Japan), 1989 Loma Prieta (San Francisco, California) and most recently 2011 Christchurch (NZ).

Geotechnical earthquake engineering practice's understanding of liquefaction is increasing with every real world example earthquakes from the mid 1960's to the current findings coming out of the 2011 Christchurch event. The gradual growth in understanding has meant that as a practice, liquefaction risk has been missed in design of many high importance/high consequence lifeline infrastructure, such as San Francisco's Bay Area Rapid Transit Tunnel and the Massey Tunnel in Vancouver. At the time of their design, earthquake ground shaking was considered, but liquefaction was not considered significant to their performance.

Current building codes do not focus on earthquake resilience, but rather life-safety. This means significant damage is allowed as long as this one code objective is met. It is therefore not surprising that when a major earthquake strikes an urban region the losses are large, and the general public is left to wonder why. The Christchurch earthquake in February 2011 is a prime example. Although liquefaction generally does not pose a significant life safety hazard, the long-term economic impact, largely related to population loss, from inoperable infrastructure will be considerable. Ten years after the 1995 Kobe earthquake the major port's production was reported to be 80% of quake levels and the population is still 10 years from recovering to normal levels. The cost to Christchurch was estimated to be NZD $40 Billion, representing some 25% of NZ's GDP in 2010 and the city is undergoing a long rebuild process.

Although low seismicity regions, such as Australia and Eastern US, are considered to have a relatively low seismic hazard compared to active tectonic areas of the world, earthquakes do occur and where susceptible geological conditions exit, liquefaction can trigger. In fact, liquefaction has been documented in many stable continental regions from small events such as 1903 Ml 5.3 Warrnambool, Australia, and 1884 M5.0 Rockaway Beach, New York where some buildings tilted and settled into the sand (Tuttle and Seeber, 1989).

In practice, the low seismicity creates a situation where liquefaction triggering is marginal at design hazard levels and very sensitive to the derivation of the seismic inputs. This paper considers the sensitivity and need for interpretation of seismic loading inputs for liquefaction assessment in low seismicity regions and discusses resilient geotechnical design implications.

Liquefaction Trigger Methodology Background

Liquefaction assessment methodology has been well established in earthquake engineering practice following Seed and Idriss (1971) and refinement over the last 40 years. The resistance to liquefaction depends on the relationship between the *in-situ* density of the soil with respect to its critical state, as well as the behavior of the soil under earthquake-induced cyclic loading.

Seed and Idriss (1971) proposed a 'simplified procedure' for evaluation of liquefaction triggering that compare the soils' resistance to liquefaction, termed cyclic resistance ratio (CRR), with the cyclic stress caused by an earthquake (e.g. seismic loading), termed cyclic stress ratio (CSR), expressed as the factor of safety (FS_{liq}) against triggering liquefaction.

$$FS_{liq} = CRR/CSR \tag{1}$$

FS_{liq} greater than 1.0 implies that liquefaction triggering is unlikely to occur.

The *CRR* is typically evaluated from correlations based on penetration resistance using standard penetration tests (SPT) or cone penetration tests (CPT) or from laboratory testing on high quality samples. Empirical relationships have been produced by correlating the normalised and corrected SPT $(N_1)_{60}$ (Youd et al. 2001, Cetin et al. 2004, Idriss and Boulanger 2008, Boulanger & Idriss 2014), and CPT q_{c1N} (Robertson and Wride 1998, Moss et al., 2006, Idriss and Boulanger 2008, Robertson 2009, Boulanger & Idriss 2014), shear wave velocity (Andrus and Stokoe 2000, Kayen et al. 2013) and seismic dilatometer parameters (Marchetti et al., 2008) with the estimates of the *CSR* of a number of sites which had or had not exhibited liquefaction during major earthquakes in the past (Youd et al., 2001; Seed et al., 2003). Discussion of the state of practice with regards to estimating *CRR* or uncertainty in the estimate is beyond the focus of this paper.

The *CSR* used in the simplified procedure for liquefaction triggering analysis is average, or equivalent, shear stress induced by a M7.5 earthquake, normalized by the in-situ effective vertical stress. It is the uncertainty and lack of guidance in derivation of seismic inputs (e.g. ground motions and design magnitude) input to liquefaction assessment that this paper explores.

Design Code Liquefaction Assessment Guidance in Low Seismicity Areas

In active seismic regions, most seismic design codes require the assessment of liquefaction hazard and provide specific guidance on the assessment methodology. For example ASCE 7-10 requires a Geotechnical Investigation Report, for high risk structures, with an assessment of consequences of soil strength loss, including slope instability, liquefaction, total and differential settlement, surface displacing due to faulting or seismically induced lateral spreading or flow.

ASCE 41-04, seismic evaluation of existing buildings, requires that liquefaction susceptible, saturated, loose granular soils that could jeopardize the building's seismic performance shall not exist in the foundation soils at depths within 50 feet (~15m) under the building for Life Safety and Immediate Occupancy. If these are encountered a detailed study is required.

Eurocode 8 Part 5 (2004) requires liquefaction to be assessed when thick layers of saturated loose sand (with or without fines) occur at a site, and specifies the liquefaction triggering methods to be used to evaluate the hazard.

Prior to the recent earthquakes in Christchurch, the New Zealand building codes were not explicit about consideration of liquefaction hazard, with the NZ building verification method document B1/VM4 lacking reference to liquefaction or its consideration, and the earthquake loadings code NZS1170.5 explicitly excluding liquefaction hazard from consideration in the document. Due to this lack of codified guidance, the NZ Transport Agency Research Report 553 – "The Development of Guidance for Bridges in New Zealand for Liquefaction and Lateral Spreading Effects", was developed to present a clear set of available procedures for analysis and design of bridges based on most recent research findings. In addition the NZ Geotechnical Society published guidelines for assessing liquefaction hazard in June 2010, only 3 months prior to the 4 September 2010 Canterbury earthquake (NZGS 2010). A recent development following the 2011 Christchurch Earthquake is the implementation of liquefaction settlement/lateral spread displacement tolerances in the building codes by the NZ government (MBIE 2012) with specific focus on the Christchurch rebuild. These define vertical and lateral displacements limits to varying degrees under SLS and ULS events according to liquefaction risk maps that need to be addressed in the design. Structures in areas identified to have moderate to significant land damage from liquefaction require a site-specific investigation.

To contrast, in Australia AS1170.4 (2007), similar to the deficiencies in NZS1170.5 (2004), only considers the impact of ground shaking on structures, and not the adverse effects from related earthquake phenomena such as settlement, slides, subsidence, liquefaction or faulting (i.e. geohazards). Seismic design for infrastructure (bridges, roads, wharfs, tanks, pipelines) is formally excluded from AS1170.4 (2007), but many infrastructure specific codes, such as AS5100.2 Bridge Code, refer back to AS1170.4 for the basis of mitigating the seismic hazard by design. AS5100.2 guidance on liquefaction is limited to stating that the possibility of soil liquefaction shall be investigated where saturated sandy and silty soils within 10m of the ground surface have SPT N <10.

Risk level

The design ground motion is determined from an ‘acceptable risk’ of the hazard being realized over the lifetime of a structure. For a design life of 50 years at a 90% confidence level (10% exceedance of design) the annual probability of exceedance is 1/475 rounded off to 1/500.

In practice there often is conflicting guidance in the derivation of design annual probability of exceedance that requires consideration and interpretation. This is exemplified in Australia where conflicting guidance for return period for a bridge with essential emergency responsibility exists (Importance Level 4, Bridge Design Class 4). The Australian Standard AS5100.2 (Bridge Code) and the Austroads Bridge Design Guidelines for Earthquake (2012) provide conflicting advice.
To add to the confusion, AS1170.4 (from AS1170.0) suggests a 1/2500 annual probability of exceedance for an Importance Level 4 structures, yet the Building Code of Australia (2014) suggests a 1/1500.

As seismic design practice is starting to redefine its approach in a resilience context, in low seismic regions the traditional return period approach is being abandoned to consider the greater consequence of the damage beyond the immediate life safety or damage to the structure. This draws on performance based design concepts. To this end, future codes are expected to include a broader focus on not merely collapse prevention (life safety) during rare earthquakes, but also damage control during less rare events (reduced downtime for repairs), and immediate occupancy following frequent events (fully operational). This design philosophy is called performance based design.

Resilient earthquake design initiatives such as REDi (Almufti 2014) are owner driven and not by code or insurance. Recent legislature has started to address this disconnect such as in Victoria, Australia with the 2014 Critical Infrastructure Resilience Act which requires owners/operators of critical infrastructure assessed as ‘vital’ to comply with mandatory obligations based on a ‘Resilience Improvement Cycle’.

Ground motion and soil site responses

In low seismicity regions there are fewer earthquakes, less rigorous seismographic networks, limited strong ground motion recordings, and greater uncertainty on maximum magnitude estimates leading to a challenges in probabilistic seismic hazard analysis (Leonard et al., 2014) and greater epistemic uncertainty.

In addition, the earthquake ground motion observed at soil sites can be substantially different from bedrock sites general provided in national codify hazard maps. The overlying soil deposits modify the earthquake induced bedrock motion as the motion is transmitted up through the soil profile to the ground surface. This modification is known as the site response effect and is a function of the soil profile geometry, the dynamic soil properties (strain-dependent shear modulus and damping) and state (density, confining stress) and the characteristics of the earthquake excitation (frequency content, amplitude, duration).

Most seismic codes, provide scaling factors to adjust the bedrock ground motions following site soil properties. The soil profile is classified into a Site Class based on soil properties defined by the natural frequency of the soil profile estimated by geotechnical investigation. Franke et al. (2014) notes often engineering practitioners correlate the site classification to some other in-situ exploration method, which may increase their input ground motions by as much as 56% and could very well be the cause of their low computed factors of safety.

Another method for calculation *CSR* directly for liquefaction analysis is a site response analysis using analysis software that considers soil non-linearity inherently (strain dependent stiffness and damping), e.g. SHAKE (Schnabel et al. 1972), Deepsoil (Park and Hashash, 2008). Site response analysis involves propagating an earthquake ground motion record, representing the bedrock ground motion, through the soil column to calculate the peak shear stress with depth profile. In practice site response analysis in low seismicity areas is not common and is lacking in both experienced practitioners and guidance. In addition, the selection of earthquake ground motions time histories has it challenges due to the epistemic uncertainty in the PSHA that defines the bedrock ground motion.

Design magnitude in low seismicity areas

For liquefaction triggering assessments in low seismicity areas, such as Australia, a critical input parameter often missing is the earthquake design magnitude. The design magnitude defines the duration weighting factor (representing the number of shaking cycles) and is included in the calculation of the non-linear shear stress reduction factor with depth. In active seismic regions around the world, local seismic design code often provides specific guidance on the selection of appropriate design earthquake magnitudes to estimate a *CSR*. For example ASCE 7-10 recommends using the maximum considered earthquake (MCE) available from the US National Hazard Map (USGS) and post-Canterbury Earthquake practice in NZ following NZS1170.5 and MBIE 2012 guidelines specify M7.5 for all liquefaction calculations regardless of the importance level.

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 estimating mean values from regional recurrence curves (Mitchell and Moore, 2007), using the maximum historic earthquake in Australia for a given region, consideration of a range of magnitudes (Yang and Wright, 2010) or choosing a conservative magnitude based on professional judgment.

Mote and So (2013) show in the low seismicity of Australia, liquefaction triggering is sensitive to earthquake design magnitude. Figure 1 shows that for a sand profile in a site soil sub-class D, with a typical bedrock PGA values in Australia (e.g. 0.08g for Sydney) the selection of a design magnitude above or below a M6.5 will determine whether liquefaction will be triggered. The lack of rigor in guidance on how to select design magnitude in Australia creates significant uncertainty in the liquefaction triggering assessments.

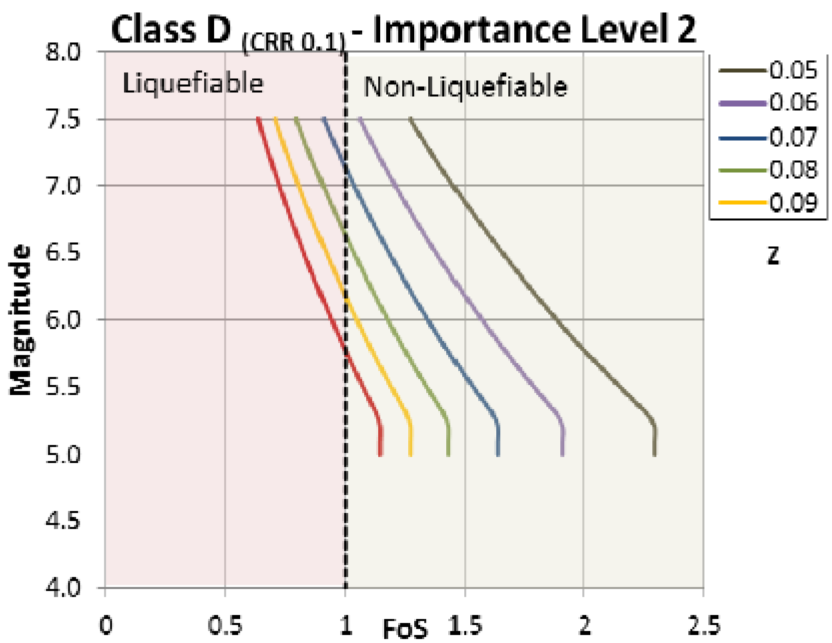

Figure 1: Sensitivity of liquefaction from Design Ground Motion.

Where design magnitudes are not explicitly provided by code, the common method for selecting magnitude is to consider the probabilistic earthquake scenarios that contribute the greatest amount to the ground motion hazard (CalTrans 2012), by examination of the magnitude deaggregation of the PSHA. In high seismicity areas, where the seismic sources are well defined, close and activity is high, this approach is considered good practice. In low seismicity areas, where seismic sources have greater uncertainty, lower activity, and are at a greater distance, considerable interpretation is required to understand both under and over conservatisms in magnitude selection.

To understand application of the seismic hazard in Australia, Dismuke and Mote (2012) developed an approximate magnitude distance deaggregation of the PSHA from AS1170-4 (2007). The results showed that in the probabilistic modelling of scenario earthquakes, the very close and small earthquakes contribute greatest to the seismic hazard and magnitudes between ~5.0 and 5.5 were the greatest contributor for the 1/2500 design event. As this design level is supposed to represent the rare event for essential and emergency structures, there was a disconnect from the maximum magnitude estimates for the Australian stable continental region (SCR) derived from paleoseismicity (Clark et al. 2010) with magnitudes between 7.0 to 7.5, but with return periods exceeding 10,000 years. This disconnect is important to understand in resilience design as the consequence of rare events to critical infrastructure are considered.

Franke et al. (2014) demonstrates how the input ground motions may bias liquefaction triggering analysis in areas of low seismicity, by considering the probabilistic ground motion deaggregation plot corresponding to a return period of 2,475 years for a hypothetical site near downtown Cincinnati and shows that nearly 80% of the 0.067g comes from nearby (<150 km) 6.3 events and only about 20% of the 0.067g is attributed to large magnitude 7.7 events originating in the New Madrid seismic zone. Considering a design basis of 2,475 years, the pairing of PGA of 0.067g exclusively with large scenario earthquakes in the New Madrid fault zone, located more than 450km away, will compute a larger liquefaction triggering hazard for a site than actually exists.

Resilience Considerations

Current building codes do not focus on earthquake resilience, but rather life safety. This means significant damage is allowed as long as the code objective is met. It is therefore not surprising that when a major earthquake strikes an urban region the losses are large and the general public is left to wonder why. Although liquefaction generally does not pose a significant life safety hazard, the economic impact from inoperable infrastructure will be considerable. In the long-term, the delayed recovery of lifeline infrastructure (water, transportation, communication) will lead to population loss.

As resilience is focused on the recovery of the community as a system after an event, the need to have essential infrastructure working is easy to understand. Considering ground effects (such as liquefaction) are critical to designing for resilience. In areas of high seismicity, the design of infrastructure explicitly considers ground impact, in low seismicity areas the uncertainty and guidance is lacking, yet the practice is starting think about resilience beyond the code.

The disconnect between the risk of earthquake and the low seismicity of a region, can be exemplified by an earthquake of magnitude 6.0-6.5 in the Sydney region of Australia is viewed by the global insurance community as one of the top 40 risks it faces worldwide from natural disasters (MacPherson et al., 2013).

The long-term cost and society implications for the wider community are not used in the code-based seismic design practice. Resilience considerations in seismic design for infrastructure need to ask if society will accept damage to a bridge, tunnel or water network that may take months or even years to repair. What would the impact on its community be? And what would the long-term economic impact be?

In high seismicity regions this can be exemplified with the immersed tube tunnels in San Francisco and Vancouver, both found to have a liquefaction risk that was considered not acceptable which led to upgrade or replacement, respectively. Both of these are located in high seismicity areas, so the decision to mitigate these lifeline infrastructure are easy to understand. Now consider the Sydney Harbour Tunnel, another immersed tube built by the same method of sinking a tube onto unconsolidated backfill and in parts very loose to loose marine sands (Pells and Wong, 1990), but located in Sydney where seismicity is much lower. If the rare earthquake happened in Sydney, triggering liquefaction and the tunnel was not functioning, the long-term economic impact to Sydney would be huge. It is easy to envision business moving elsewhere and population loss as already long commute times double for years to come. When assessing this lifeline/emergency response structure would considering a magnitude <5.5 for a return period of 2,500 years that does not trigger liquefaction seem appropriate or would a maximum credible earthquake of magnitude 7.3 that would trigger allow for a more resilient community?

Conclusions

Although liquefaction generally does not pose a significant life safety hazard, the long-term economic impact and population loss from inoperable infrastructure will be considerable.

Low seismicity regions create a situation where liquefaction triggering is marginal at design hazard levels and sensitive to the derivation of the seismic inputs. The selection of design event magnitudes are often not provided in seismic design codes in low seismicity regions and the application of magnitude-distance deaggregation to select this events is problematic. Interpretation of the basis seismic hazard inputs is required to understand the risk.

The resilience of a community can be directly related to the performance of its infrastructure. Current seismic design practice is starting to look beyond code to resilience, and the consequence of liquefaction risk on the recovery of the greater community. Understanding risk, uncertainty, and over/under conservatism in design is important in a resilience context.

Currently a resilient seismic design approach has not been codified, but legislation is starting to come into place which requires owners/operators of critical infrastructure to comply with mandatory obligations based on a resilience framework.

Ultimately it is up to the geoseismic practitioner to understand liquefaction risk and the uncertainties in assessment procedure and seismic inputs in low seismicity regions. For critical infrastructure a resilient approach should be considered where consequence to the greater community is evaluated and performance based design allows rapid functional recovery.

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