GIS-based Microzonation for Liquefaction-induced Ground Damage in Auckland Region

O. Altafi), L. Wotherspoonii), R. P. Orenseiii), S. van Ballegooyiv) and R. Robertsv)

i) PhD Student, Dept of Civil & Environmental Engineering, University of Auckland, Private Bag 92019, Auckland 1142, NZ.
ii) Senior Lecturer, Dept of Civil & Environmental Engineering, University of Auckland, Private Bag 92019, Auckland 1142, NZ.
iii) Associate Professor, Dept of Civil & Environmental Engineering, University of Auckland, Private Bag 92019, Auckland 1142, NZ.
iv) Technical Director, Geotechnical Division, Tonkin + Taylor Ltd., 105 Carlton Gore Rd, Newmarket, Auckland 1141, NZ.
v) Geotechnical and Geological Practice Lead, Auckland Council, Private Bag 92300, Auckland 1142, NZ.

ABSTRACT

Although Auckland is one of the country's least seismically active regions, the earthquake hazard in the region cannot be disregarded given the potential social and economic impacts. As part of this, a good understanding of the co-seismic hazards across the region is of key importance. This paper presents on the methodology adopted for the GIS-based microzonation for liquefaction hazard across the Auckland region and the updated liquefaction-induced ground damage maps based on the recently developed MBIE guidance. Geology-based screening is initially applied across the region to identify areas where liquefaction is unlikely, with a separate categorisation for alluvial deposits with volcanic content in this region. The remaining areas are classified as “liquefaction damage is possible”, a broad classification that can only be refined where additional data is available. Borehole-based investigation data and elevation details are used to further screen out areas where non-liquefiable deposits are present. Where CPT soundings and groundwater data are available, detailed liquefaction assessments are carried out that enable refinement of classification beyond the high-level geology-based screening. LSN values for 100- and 500-year return period ground motions are used to classify areas where similar geotechnical conditions are present with liquefaction vulnerabilities ranging from very low to high. With these multiple approaches, regional liquefaction-induced ground damage maps are developed for Auckland region for different levels of investigation detail.

Keywords: liquefaction hazard, earthquake, ground damage maps, GIS

1 INTRODUCTION

It is generally considered that Auckland Region is one of New Zealand’s least seismically active regions, located approximately 300 km away from the boundary between Australian and Pacific tectonic plates (Kenny et al., 2011). In the GNS Active Faults Database (GNS 2017) there is only one fault identified in close vicinity to the Auckland Region, the Wairoa North Fault, approximately 30 km from the Auckland Central Business District. However, recent recognition of at least one active fault close to the urban area, the Drury Fault, has changed the perception of seismic hazard (Al-Salim, 2000; Edbrooke et al., 2003). Moreover, faults further afield, such as the Kerepehi Fault in the Hauraki Plains, have the potential to generate damaging ground motions within the Auckland region. According to the 2013 Census, the population of Auckland region is about 1.4 million and Auckland is the hub of New Zealand’s major commercial activities (Auckland Council, 2014). As such, the seismic and co-seismic hazards in the region cannot be disregarded given the potential social and economic impacts.

In geotechnical engineering, an important aspect of the seismic design process is the assessment of the potential for liquefaction-induced ground damage. Consequences of liquefaction may prove to be costly and severe, as was seen in 2010-11 Canterbury earthquake sequence (Cubrinovski et al., 2011) and the 2016 Kaikōura earthquake (Cubrinovski et al. 2017, Stringer et al. 2017). Regional assessment of liquefaction susceptibility was last undertaken in 1997 as part of the Auckland Engineering Lifelines Project – Stage 1 (ARC 1997), prior to the recent advancements in the understanding and assessment of liquefaction susceptibility and surface manifestation severity. The focus of the ongoing research project presented in this paper is the development of liquefaction-induced ground damage maps for the Auckland region based on the recently released Ministry of Business, Innovation and Employment (MBIE) National Framework for Assessment of Liquefaction-Induced Ground Damage to Inform Planning Processes (MBIE 2017). This paper
presents an overview of the methodology and the categorisation approach based on different levels of assessment detail. A key aspect of this mapping is the presence of Auckland’s volcanic deposits, and these deposits have been identified separately from other soil types for future more detailed assessment of their liquefaction vulnerability.

2 METHODOLOGY AND CATEGORISATION APPROACH

Figure 1 summarises the liquefaction-induced ground damage assessment methodology for Auckland region as recommended by MBIE. The first step is to identify the purpose and the level of detail for the assessment required. In this project, Level A and Level B assessments are the focus and are typically based on broad regional-scale ground information, such as geological maps and groundwater models supplemented with local knowledge. Therefore, initial stages of the project included collation of geological, geotechnical and hydrological data available in Auckland region. By starting with coarse datasets, such as geological maps and digital ground elevation models, the project carried out a step-by-step elimination of areas where deposits that were unlikely to liquefy were present. The remaining areas were then assessed using geotechnical site investigation data to provide a better representation of material properties using investigation data from the New Zealand Geotechnical Database (NZGD) and other available sources. The most detailed assessment utilised cone penetration test (CPT) soundings to develop ground damage response curves for areas across the city and provided a finer level of categorisation of potential for liquefaction-induced ground damage. In this project, three levels of map categorisation were adopted:

1. Geology-based screening
2. Geotechnical investigation and elevation-based screening
3. CPT-based liquefaction assessment

The details of each of these levels of categorisation are described in the following sections. The data from each of these levels were used to define the recommended liquefaction vulnerability categories in the MBIE guidelines summarised in Figure 2. As the level of information available increases, the precision of categorisation can also increase, shifting from a two-category framework for high-level data (1 and 2 above) to a four-category framework where liquefaction assessments using site investigation data are undertaken (3 above).

For both initial geology-based screening (Level 1) and detailed CPT based investigation (Level 3), peak ground acceleration (PGA) characteristics were defined using the NZTA Bridge Manual SP/M/022 (2013), The PGA values to be applied are ‘unweighted’ and derived for the magnitude (Mw) of 5.9 for the Auckland region defined
2.1 Geology based screening

A geological desk study assessment was undertaken based on published geological maps, Auckland volcanic field mapping and published reports for different projects in the region. Q-Maps developed by GNS (2017) were used as the basic input in ArcMap10.4 (ESRI 2011) to create geological layers for Auckland Region. Similarly, data related to the Auckland volcanic field, with spatial layers identifying basaltic deposits in the Auckland region, were also used. The output of this initial assessment was a geology-based potential liquefaction ground damage map illustrating areas in the Auckland Region with deposits for which “liquefaction damage is possible” and “liquefaction damage is unlikely”. By considering the regional seismicity and depth to groundwater in conjunction with the depositional process and the age of soil deposits, the semi-quantitative screening criteria in Table 1 was used to identify geological units where significant liquefaction-induced ground damage was unlikely to occur. A soil deposit of the specified type was assigned a liquefaction vulnerability category of “liquefaction damage is unlikely” if the 500-year peak ground acceleration (PGA) was less than the value listed for each depositional age. Figure 3 illustrates the summary of results of geology-based screening stage.

**Soil deposits where liquefaction damage is unlikely**

In general terms, the basement, Late Pliocene, and Early Pleistocene rocks are lithified or relatively well consolidated and will not liquefy under strong ground shaking. Because of their age, the early and middle Pleistocene non-marine and marine deposits, the last interglacial marine deposits, and the alluvial materials of the early and middle last glaciation are old enough to have been consolidated by natural processes and their liquefaction susceptibility is regarded as negligible (Youd and Perkins 1978). Using Table 1 and this criterion, the following regional deposits were assigned to the category “liquefaction damage is unlikely”:

- Greywacke basement rock
- Tuff
- East Coast Bays Formation, containing sandstone and mudstone deposits
- Basalt and scoria
- Firm to stiff Pleistocene age alluvium

**Soil deposits where liquefaction damage is possible**

Soil types susceptible to liquefaction include fills, reclaimed land, sand, silts, quaternary deposits and estuarine deposits of Holocene age (Pyke 2003; Youd et al., 2001; Youd and Perkins, 1978). Most liquefaction-induced failures and nearly all case history data compiled in empirical charts for liquefaction evaluation were in Holocene deposits or constructed fills (Seed and Idriss, 1971; Seed et al., 1985; Boulanger and Idriss, 2004).

Based on Table 1 and the above discussion, the following geological deposits were categorised as “liquefaction damage is possible”:

- Fills / reclaimed land
Sand, silt, gravel and swamp deposits of Holocene age

Volcanic deposits

The volcanic deposits in the Auckland region are of “Late Pliocene to Middle Pleistocene” geological age, except for the deposits at Mt Wellington and Purchase Hill (Leonard et al., 2017). Basalt, scoria and tuff deposits were assigned to “liquefaction damage is unlikely”. Sandy, silty volcanic soils with tephra, pumice, and lignite may be susceptible to liquefaction depending on the geological age, depth to groundwater and earthquake shaking based on historical evidence from different regions of the world (JSCE-JGS, 2003; Uzuoka et al., 2005; Crenairz 2010). Following the semi-quantitative criteria presented in Table 1, all volcanic deposits in Auckland region would fall under the category “liquefaction damage is unlikely”.

However, the 1987 Edgecumbe earthquake, for example, showed widespread liquefaction of sands of volcanic origin. Similarly, there are some earthquake events when damage due to liquefaction was observed in volcanic soils in other countries. For example, failed soils of volcanic origin were reported in 2003 Sanriku-Minami Earthquake in Tohoku, Japan, it behaved like mud and flowed laterally (JSCE-JGS, 2003; Uzuoka et al., 2005). February 27, 2010, Maule, Chile earthquake manifested soil liquefaction along the shore of the Villarica Lake Temuco (Crenairz 2010). Therefore, in order to have further confidence in the screening process, and to allow for future assessment of these deposits as the understanding of their liquefaction susceptibility improves, the sandy, silty deposits with tephra, pumice and lignite deposits were assigned to “liquefaction damage is unlikely (alluvial with volcanic content)”.  

2.2 Topographic and geotechnical investigation-based screening

The initial geology-based potential liquefaction-induced ground damage map was further refined using soil classification and water table data from geotechnical site investigations and topographic elevation data. This process was undertaken to confirm the categories assigned based on the geology-based approach and to reclassify areas where appropriate. Here the focus of the geotechnical investigation data based screening was...
information from boreholes, as CPT data was used in the subsequent assessment stage. Geological maps only provide a classification of soil deposits based on surface geology and do not account for the overall subsurface stratigraphy. As elevated soils may have greater depths to the water table, screening was also carried out using elevation data, combined with measured water table from site investigation data. Similarly, volcanic deposits classified as “Liquefaction damage is unlikely (alluvial with volcanic content)” in the geology-based map were assessed in the geotechnical and elevation screening stage to confirm this classification. In order to get an overall view of the elevated potentially liquefiable deposits, areas with an elevation above 20 m were highlighted to provide a high-level representation of the topographic characteristics across the region. Topographic contours were overlaid on the areas of interest to analyse these deposits in more detail, with smaller focus areas defined across the region. Figure 4 depicts the process utilised in this stage of the investigation, with a summary of focus areas overlaid on a map showing high and low elevations within the different mapped categories. One of the focus area (Area 8) is zoomed in the figure to show topographic contours and the location of geotechnical investigations in this area.

![Image](42)

**Fig. 4. Summary of elevation and geotechnical investigation stage: map showing low and high elevation deposits with focus areas. Focus area 8 is zoomed-in to show topographic contour details and location of available geotechnical investigation data.**

### 2.3 CPT-based liquefaction assessment

The areas classified as “liquefaction damage is possible” and “Liquefaction damage is unlikely (alluvial with volcanic content)” in previous stages using higher level methods were further investigated using a detailed CPT-based liquefaction assessment methodology. The analysis is performed using a probabilistic approach, i.e. varying PGA values for a fixed magnitude of the earthquake. The Boulangar and Idriss (2014) liquefaction triggering methodology was used in conjunction with the Liquefaction Severity Number (LSN) to estimate the potential liquefaction-induced land damage (van Ballegooy et al., 2014). Following the NZTA Bridge Manual SP/M/022, the peak ground accelerations (PGA) defined previously were used with an earthquake magnitude of Mw5.9. A groundwater model for the region was developed for triggering analysis, using available investigation data, monitoring wells and other hydrogeological information, with models developed to represent the temporal variation in groundwater where possible. Figure 5 presents conceptual examples of ground damage response curves for liquefaction-induced ground damage to be used in liquefaction vulnerability categorisation, providing a visual representation of the relationship between liquefaction-induced ground damage and intensity of
earthquake shaking. For example, if less than minor ground damage at 500-year level of shaking, then the liquefaction vulnerability category is “Low” (Curve 1 in Figure 5) and if more than Minor ground damage at 100-year level of shaking, then the liquefaction vulnerability category is “High” (Curve 3 in Figure 5). Ground response curves using LSN values similar to conceptual example shown in Figure 5 are being developed for all individual CPT soundings within each focus area with more detailed definitions of minor, moderate and severe damages. The output of this stage will give precise liquefaction vulnerability categories for the Auckland region.

![Conceptual example of ground damage response curves for low, medium and high liquefaction vulnerability categories, and performance criteria for liquefaction categorisation (MBIE 2017).](image)

**3 CONCLUDING REMARKS**

In this paper, the process for the development of GIS-based microzonation of liquefaction-induced ground damage for the Auckland region have been presented. Extensive geological and geotechnical investigation data was employed to identify deposits where liquefaction damage is possible. On the basis of initial results of different levels of investigations and ground damage response curves, liquefaction-induced ground damage maps are being developed considering MBIE guidelines. Preliminary results show that:

- For a large part of the Auckland Region, there were no geotechnical investigation data to further assess the geology-based classification. Therefore, these areas were assigned the high level “Liquefaction damage is possible” categorisation.
- Similarly, alluvial deposits with volcanic content which cover a large portion Auckland region were classified separately and investigated, but more detailed investigation may be required to fully understand the liquefaction vulnerability of these deposits.
- Detailed investigation using CPT soundings in the areas where data is available will be useful to determine the precise liquefaction vulnerability categories from “Very Low” to “High” for the whole region.

The maps developed in this project along with detailed results and recommendation will benefit planners, asset owners, emergency managers, and engineers in assessing the vulnerability of their projects and assets with respect to the liquefaction of soil. It is expected that these maps may be used to identify the need for detailed site-specific studies. Given the low accuracy of the geological maps used for screening, a ‘liquefaction is unlikely’ classification from this study will need verification by an engineering geologist or geotechnical engineer before detailed design work is commenced.

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