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Influence of geologic and geotechnical dataset resolution on regional liquefaction assessment of the Lower Wairau Plains

Influence de la résolution des ensembles de données géologiques et géotechniques sur l'évaluation régionale de la liquéfaction dans les plaines du Bas-Wairau.

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ABSTRACT: The Wairau Plains are located in the north-east of the South Island of New Zealand, with alluvial deposits of fine-grained silts and sands combined with low-lying topography suggesting the presence of liquefiable deposits over significant portions of the region. Liquefaction manifestations were observed in past earthquakes including the 1848 Marlborough and 1855 Wairarapa earthquakes, and more recently during the 2013 Lake Grassmere and 2016 Kaikōura earthquakes. Therefore, a good understanding of the deposits that may be susceptible to liquefaction is important for land use planning in the region and to allow developers and asset owners to appropriately address their risk. For this purpose, multiple approaches have been employed to develop regional-scale maps showing the liquefaction vulnerability categories for the region. After applying semi-qualitative criteria linked to geologic age and deposit type, the higher resolution surface mapping of geomorphologic characteristics encompassing the Wairau River and the Opaoa River was used for screening. A detailed basin geologic model developed for groundwater modelling was analyzed to provide a higher level of resolution than the surface-geology based classification. This is used to identify the thickness of near-surface gravel deposits, providing an improved understanding of the presence or lack of potentially non-liquefiable crust deposits. This paper describes the methodology adopted for this project and focuses on the influence of geomorphic characteristics and analysis of the detailed geologic basin model on the liquefaction classification of the Lower Wairau Plains.

RÉSUMÉ : Les plaines de Wairau sont situées dans le nord-est de l'île du Sud de la Nouvelle-Zélande, avec des dépôts alluviaux de limons et de sables à grain fin combinés à une topographie de faible altitude suggérant la présence de dépôts liquéfiables sur des portions importantes de la région. Des manifestations de liquéfaction ont été observées lors de séismes passés, notamment les séismes de 1848 à Marlborough et de 1855 à Wairarapa, et plus récemment lors des séismes de 2013 à Lake Grassmere et de 2016 à Kaikōura. Par conséquent, une bonne compréhension des gisements susceptibles de subir une liquéfaction est importante pour la planification de l'utilisation des terres dans la région et pour permettre aux promoteurs et aux propriétaires d'actifs de traiter de manière appropriée leur risque. Dans ce but, de multiples approches ont été utilisées pour développer des cartes à l'échelle régionale montrant les catégories de vulnérabilité à la liquéfaction pour la région. Après avoir appliqué des critères semi-qualitatifs liés à l'âge géologique et au type de dépôt, la cartographie de surface à plus haute résolution des caractéristiques géomorphologiques englobant la rivière Wairau et la rivière Opaoa a été utilisée pour la sélection. Un modèle géologique détaillé du bassin développé pour la modélisation des eaux souterraines a été analysé pour fournir un niveau de résolution plus élevé que la classification basée sur la géologie de surface. Ceci est utilisé pour identifier l'épaisseur des dépôts de gravier proches de la surface, ce qui permet de mieux comprendre la présence ou l'absence de dépôts de croûte potentiellement non liquéfiable. Cet article décrit la méthodologie adoptée pour ce projet et se concentre sur l'influence des caractéristiques géomorphologiques et de l'analyse du modèle géologique détaillé du bassin sur la classification de liquéfaction des plaines du Wairau inférieur.

KEYWORDS: liquefaction, earthquake, cone penetration test, mapping, liquefaction-induced damage

1 INTRODUCTION

The Lower Wairau Plains are located in the north-east of the South Island of New Zealand in the region of Marlborough. The region is intersected by many active crustal faults such as the Wairau, Awatere, and Clarence Faults, which give rise to frequent seismic events (Rattenbury et al. 2006). The region is situated on predominantly flat to gently undulating alluvial plains. These plains are underlain by Holocene age marine and estuarine silts and sands of the Dillons Point Formation and alluvial gravels and sands of the Rapaura Formation. The soils comprising the Dillons Point Formation are observed to vary significantly in their composition and degree of consolidation (MDC 2012). The alluvial sediments on the eastern margin of the Wairau Plains are inter-fingered with lagoonal muds and coastal sands, silts, and gravels (Basher et al. 1995). Figure 1 shows the geographic location of the Lower Wairau Plains and summarizes the simplified surface geological deposits present in the region.

A number of historic earthquakes, the 1848 Marlborough and 1855 Wairarapa earthquakes, and more recently the 2013 Lake Grassmere and 2016 Kaikōura earthquakes, have produced varying modes and severity of liquefaction manifestation in the region (Stringer et al. 2017). These observed manifestations indicate that fluvial geomorphology and the depositional processes of meandering rivers are important factors for the interpretation of the distribution and sediment types in areas that are susceptible to liquefaction. In addition to surface geologic information, more detailed geomorphic characteristics are also useful for the evaluation of the liquefaction potential of soil deposits. During the Canterbury earthquake sequence, liquefaction and liquefaction-induced ground deformations were primarily concentrated near modern waterways and areas underlain by Holocene fluvial deposits with shallow water tables (< 1 to 2 m). In southern Christchurch, spatial variations of liquefaction and subsidence were documented in the suburbs within inner meander loops of the Heathcote River (Grace 2015). Similarly, a comparison of observed liquefaction with geomorphology in Whakatane following the Edgecumbe earthquake highlighted the importance of geomorphic setting and fluvial formations in delineating the sites susceptible to liquefaction. Liquefaction manifestation in historical events have shown that young, unconsolidated point-bar and paleo-channel deposits are highly susceptible to liquefaction, and thus are likely to liquefy during future events (Bastin et al., 2017). Therefore, geomorphological characteristics in the lower Wairau Plains are studied and their influence on potential liquefaction vulnerability categories is discussed.

Similarly, a detailed geologic basin model is utilized to define the thickness of the potentially non-liquefiable surface crust using a detailed analysis of the high-quality extensive datasets available in the region. This paper presents the findings of an on-going research project focusing on the findings of geomorphological formations and detailed geological basin model available in the region.

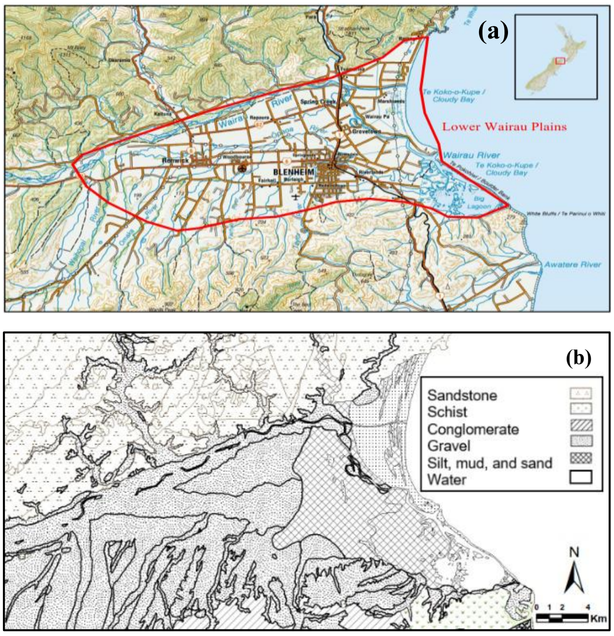

Figure 1. (a) Geographic location of the Lower Wairau plains; (b) Geologic map of the Lower Wairau Plains

2 METHODOLOGY

In order to assign liquefaction vulnerability categories in the Lower Wairau Plains, guidelines developed by the Ministry of Business Innovation and Employment (MBIE) for liquefaction assessment are followed. The first step is to identify the level of detail for the assessment so that the required data and resources can be determined. Three levels of assessment are utilized for this research, i.e., Level A, B and C. Level A is basic desktop assessment, Level B is calibrated desktop assessment and Level C is a detailed region-wide assessment. This paper presents the preliminary findings of Level A and Level B assessments only.

Level A is a basic desktop study that utilizes surface geology maps and relates soil types with liquefaction potential. To define the deposits which are potentially liquefiable, the classification by Youd & Perkins (1978) and other researchers (Pyke 2003, Youd et al. 2001) is employed. 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 summarized in Table 1 is used to identify geological units where significant liquefaction-induced ground damage is unlikely to occur. Peak ground acceleration (PGA) characteristics for the Lower Wairau Plains are defined following the New Zealand Transport Agency Bridge Manual SP/M/022 for recommended earthquake magnitude of Mw 6.1 and Mw 6.75 events by the manual (NZTA 2013). This gives the PGA characteristics for the Lower Wairau Plains equal to 0.21g for a 100-year return period and 0.43g for a 500-year return period.

In the next step, the geomorphology of the Lower Wairau Plains is studied in conjunction with the potential for liquefaction using literature related to the performance of typical geomorphological formations in recent earthquakes. The geomorphology of the lower portion of the Wairau Plains mapped by Bastin et al. (2018) is utilized as a basic input for this stage of the study. This mapping is based on the analysis of river morphologies using LiDAR, historical maps, and literature outlining drainage modification and the history of plains.

At the final screening in Level B assessment, a detailed geological basin model developed using groundwater observation wells was utilized to better constrain what deposits were present both across the plains and the variation of these deposits with depth. In this research, the model was used to determine the thickness of potentially non-liquefiable surface crust, as a thicker crust is more likely to mitigate the effects of liquefaction of underlying deposits.

Table 1: Semi-quantitative screening criteria for identifying land where liquefaction-induced ground damage is unlikely (MBIE 2017)

Type of soil deposits	**A liquefaction vulnerability category of "Liquefaction damage is unlikely" can be assigned if either of these conditions is met:**	
	PGA for the 500-year return period shaking	**Depth to groundwater**
Late Holocene age	< 0.1 g	> 8 m
Holocene age	< 0.2 g	> 6 m
Less than 11,000 years old		
Latest Pleistocene age	< 0.3 g	> 4 m
Between 11,000 and 15,000 years old		

3 RESULTS AND DISCUSSIONS

3.1 *Non-flow behavior under simple shear condition*

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. Their liquefaction susceptibility is regarded as negligible. Liquefaction-induced ground damage could be possible in alluvial deposits of fine-grained silts and sands that are present in the Lower Wairau Plains. These alluvial deposits are inter-fingered with mud, sands, silts, and gravels, and the level of detail of geologic maps is not likely to be able to differentiate between gravels and sands/silts in the region. Figure 2 shows the location of rocks and young and old alluvial deposits with varying values of depth to groundwater following the semi-quantitative criteria presented in Table 1.

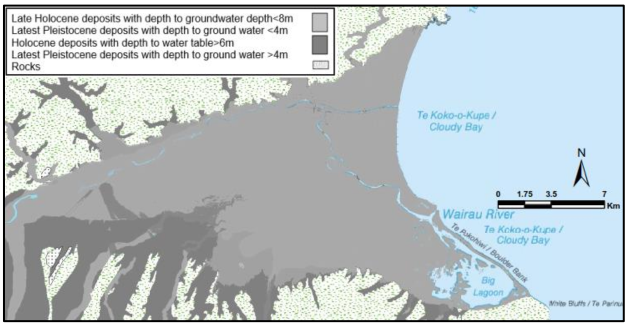

Figure 2. Geology-based liquefaction-induced ground damage map for the Lower Wairau Plains

3.2 *Geomorphological influences*

The geomorphology of the Lower Wairau and Opaoa Rivers is meandering and is characterized by a single sinuous channel that forms meander bends. The geomorphic map for the lower portion of the Wairua Plains is presented in Figure 3. The limited deposition on the outer bank and predominance of silts in the distal floodplain result in lower liquefaction susceptibilities of the underlying sediments. Point bar deposits comprise fine-grained sand grading to silt. They are found in meandering Opawa and Wairau Rivers in both active and paleochannels adjacent deposits. These deposits are also geologically young, unconsolidated and saturated, and thus are likely to liquefy during future events. A low topographic relief in the vicinity of Blenheim combined with regular flooding resulted in large swamps forming within much of the area now occupied by Blenheim. Interdune swamp deposits in the Lower Wairau Plains are composed of mainly silts with layers of peat and mud. During the 2010-11 Canterbury earthquake sequence, swamp deposits in south-western Christchurch showed less severe manifestation than what was predicted by CPT-based liquefaction triggering analysis. Crevasse splays along with point bar deposits being late Holocene deposits (age <3500 yrs. old), unconsolidated and saturated did not perform well in historic earthquake events and have a high liquefaction potential. Estuary deposits from the mainland to the estuary in the northeast towards shoreline and lagoon are silty and gravelly in nature and have a high liquefaction potential. The ridge series consists of shallow, well-drained soils that formed from semi-consolidated interbedded sandy and loamy sedimentary beds. These formations are composed of sand as well as sediment worked from underlying beach material.

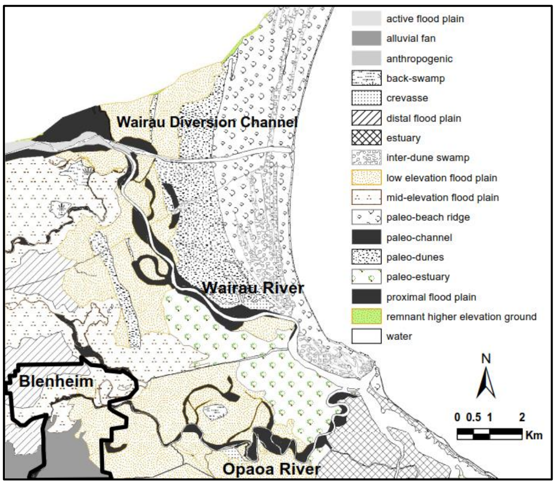

Figure 3. Geomorphological map of the Lower Wairau Plains with the geographic location of Blenheim and rivers in the region (adapted from Bastin et al. (2018))

In the south of the Wairau River, there is a single gravel ridge (the Boulder Bank) which forms a spit enclosing the Wairau Lagoons. Dune formations towards the shore are also dominated by gravel deposits. Similarly, gravel beach ridges are present from the modern coastline to 5.5 km inland, whereas discontinuous sand dunes are present from 5.5 to 7 km inland and reflect the position of the paleocoastlines. Generally, these deposits have a low liquefaction potential considering gravel-dominated material and depositional characteristics, as these are compacted by wave action. Based on available geomorphological data and the above discussion, categories of "less susceptible" and "more susceptible" are assigned and summarized in Figure 4.

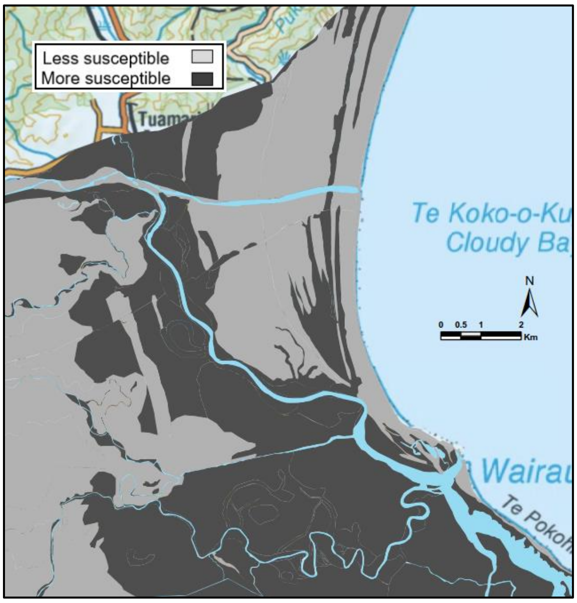

Figure 4. Summary of updated liquefaction vulnerability categories based on the geomorphology of the Wairau Plains

4 DETAILED BASIN GEOLOGICAL MODEL

Groundwater surface interactions in the Wairau Plains were studied and mapped by White et al. (2016), which led to the formation of a detailed geologic basin model. Observations of lithology from 1,165 wells were modelled to calculate the continuous 3D distribution of de-facto probabilities for the occurrence of three sediment classes, i.e., gravel, sands, and clays. Through gridding and contouring, 2D surface maps were formed, and probability values were extracted up to a 100 m depth for data points in North-south and East-West directions. For liquefaction-induced ground damage assessment, the probability of occurrence of gravel to a depth of 20 m is plotted along with the groundwater depth from an available average groundwater model in the region to confirm the presence of a thick gravel crust from the surface above the fine-grained alluvial deposits, which could prevent the surface manifestation of liquefaction. Figure 5 illustrates the location of cross-sections from the model and details of the gravel and groundwater depth for each cross-section. The final outcome of this analysis is the variation in gravel crust thickness, as illustrated in Figure 6. Effects of near-surface non-liquefying deposits against the surface manifestation of liquefaction are well documented, and observations from historic events have indicated a minimum crust thickness of 5 m could prevent the surface manifestation of liquefaction (Ishihara 1985). The analysis shows that a gravel crust of more than 5 m is present from the surface above the fine-grained alluvial deposits in the areas west and south of Blenheim.

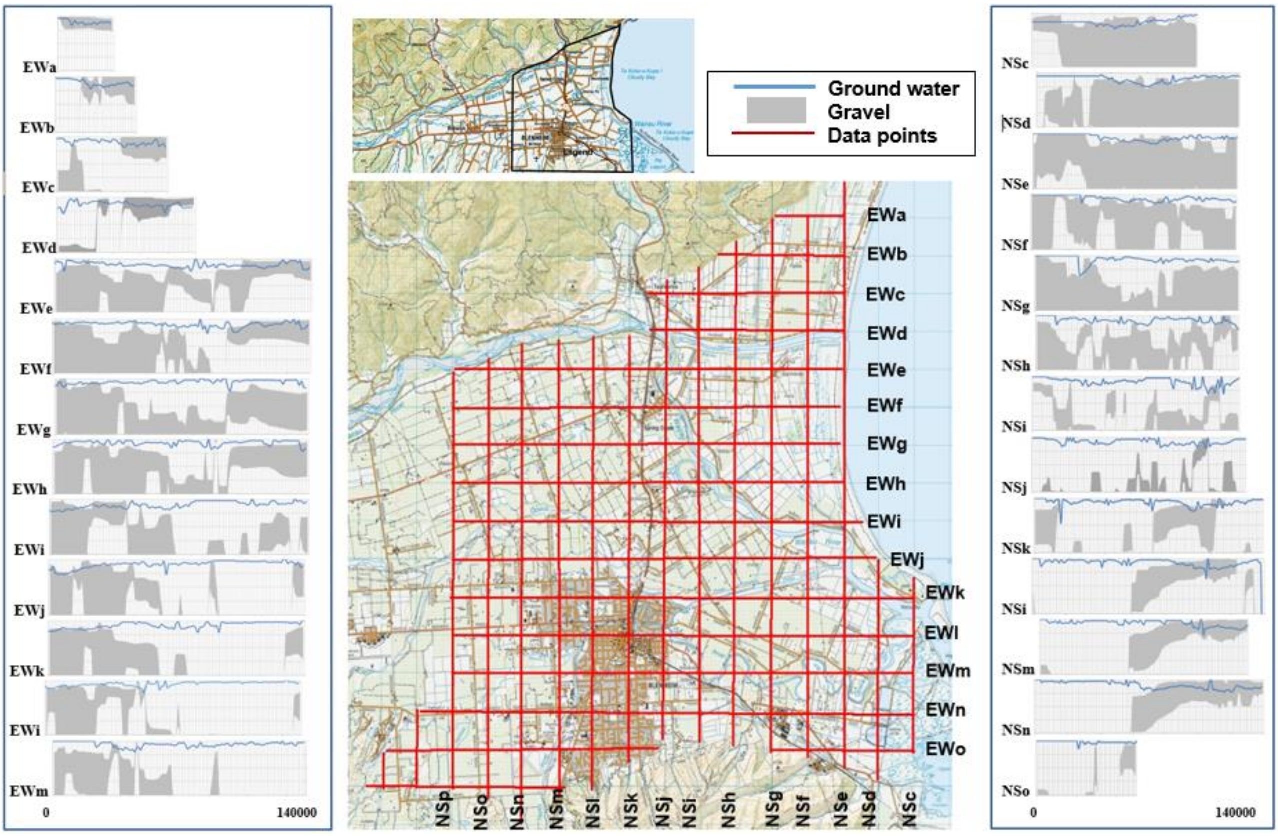

Figure 5: Profile of cross-sections in east-west and north-south directions with average groundwater levels and gravel thickness and depth to gravel for 80% probability.

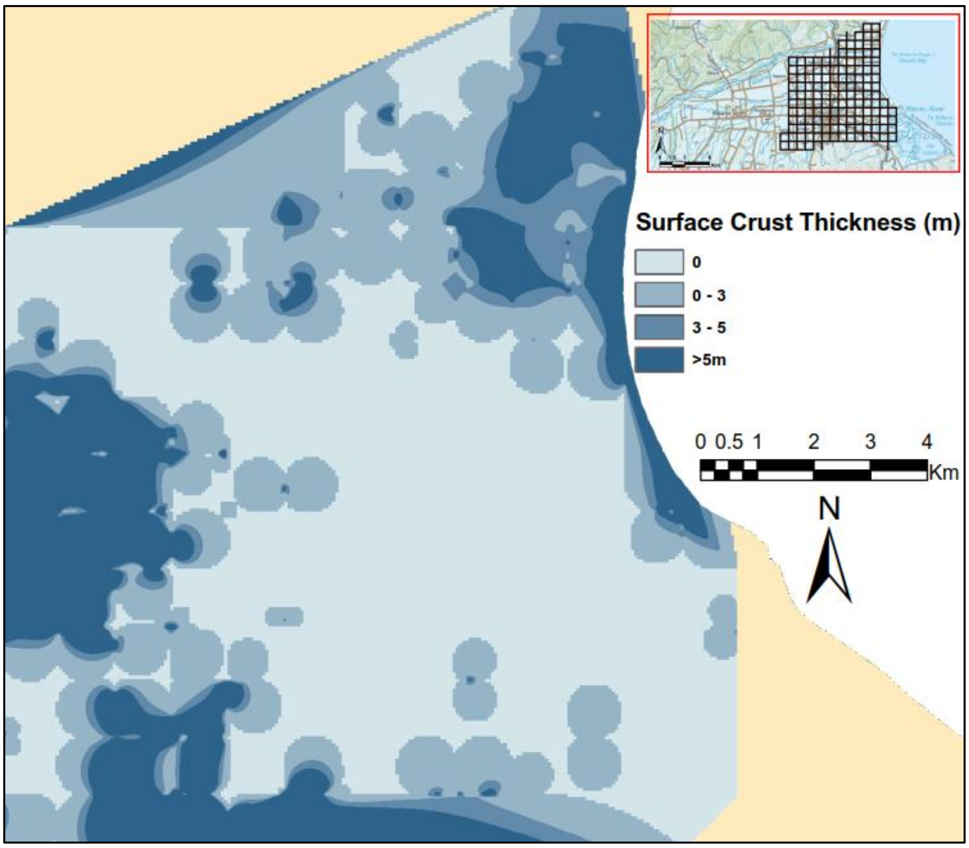

Figure 6: Summary of the detailed geologic basin model analysis showing non-liquefying gravel thickness from the surface.

5 CONCLUDING REMARKS

In this paper, the liquefaction-induced ground damage assessment of the Lower Wairau Plains has been presented with an emphasis on geomorphological and detailed geologic basin model. On the basis of preliminary results of Level A and B assessments, liquefaction-induced ground damage maps are being developed. Preliminary results show that:

- Alluvial deposits of fine-grained silts and sands are present in the Lower Wairau Plains, where liquefaction-induced ground damage could be possible. The level of detail of geologic maps is not likely to be able to differentiate between gravels and sands/silts in the region. Therefore, more detailed geotechnical datasets play a vital role in assigning a category in gravel-dominated alluvial deposits in the region.
- The detailed study on geomorphological formations in the region shows that areas with low-level flood plains, proximal flood plains, paleochannel, point bar deposits, estuaries and interdune swamp deposits could be more susceptible to liquefaction-induced ground damage as compared to other formations in the regions, including distal flood plains, paleo ridges, alluvial fans and paleo dunes.
- Analysis of extensive datasets available from the detailed geologic basin model of the region had identified areas in the west and south of Blenheim where thick non-liquefiable gravel crust is present, while some areas to the north and northwest have surface gravel layer less than 5 m. The thickness of the gravel crust at the site may affect its liquefaction susceptibility.

This research provides an initial indication of the liquefaction vulnerability of soil deposits across the region and shows the importance of geomorphological and geological dataset resolution for the liquefaction assessment in the region. As surface geological-based assessments are unable to give clear demarcation of the alluvial deposits in the region, which are intermixed and have gravel domination in certain areas, further detailed Level C assessment will give more precise liquefaction vulnerability categories in the region.

6 ACKNOWLEDGMENTS

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