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Reprint of Liquefaction assessments at shallow foundation building sites in the Central Business District of Christchurch, New Zealand

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ABSTRACT

The 2010–2011 Canterbury earthquake sequence provides an exceptional opportunity to investigate the effects of varying degrees of liquefaction on the built environment. Significant ground settlements and building damage in the Central Business District (CBD) were observed for the Christchurch earthquake. The results of CPTs and soil index tests from exploratory borings performed in the CBD are combined with cyclic triaxial (CTX) test results to characterize the soil deposits at several buildings sites. Conventional one-dimensional liquefaction-induced ground settlement procedures do not capture shear-induced deformation mechanisms and the effects of ground loss due to sediment ejecta. Improved procedures are required. Nonlinear effective stress analyses using robust soil constitutive models calibrated through CTX tests provide a means for developing these procedures. The CTX tests estimate generally consistent cyclic resistances as the CPT-based methods for medium dense sands and silty sands; however, the CTX tests provide useful insights regarding pore water pressure response and strain development. Correlations and CTX tests performed on loose clean sands indicate that these specimens were disturbed by the sampling process. Interim findings from this ongoing study are presented, and preliminary recommendations for evaluating the seismic performance of buildings with shallow foundations at sites with liquefiable soils are provided.

1. Introduction

The 2010–2011 Canterbury earthquake sequence significantly affected Christchurch, New Zealand (NZ). The Christchurch earthquake caused 185 fatalities and many serious injuries. Earthquake shaking triggered localized-to-widespread, minor-to-severe liquefaction in the Christchurch area (e.g., [1–6]). Much of the damage of multi-story buildings was within the Central Business District (CBD). Nearly half of the buildings inspected within the CBD were marked as restricted access due to potential safety issues, and most of the CBD was cordoned off for over two years after the Christchurch earthquake. A majority of the 4,000 buildings within the CBD have been demolished, including most of the city's high-rise buildings. The seismic performance of modern multi-story buildings and buried utilities in the CBD were often significantly impacted by soil liquefaction.

The objective of this paper is to describe and explain some of the damage observed within the CBD. The performance of multi-story buildings during the Christchurch earthquake is emphasized. The important role of the CPT in characterizing the subsurface conditions and in providing data for evaluating the liquefaction hazard is discussed. Cyclic triaxial testing of relatively "undisturbed" soil specimens complement the CPT data and provide useful insights. The cyclic triaxial (CTX) test results provide important insights regarding the rapid transformation of soil from a stiff to a soft response as the excess pore water pressure rises beyond a threshold value. The laboratory test results are also useful in calibrating numerical simulations. Some important findings and preliminary recommendations for evaluating buildings with shallow foundations at potentially liquefiable sites are presented.

2. Subsurface conditions within the CBD

The Canterbury Plains are composed of complex alluvial fans deposited by eastward-flowing rivers draining the Southern Alps and discharging into Pegasus Bay on the Pacific Coast. Christchurch lies along the eastern extent of the Canterbury Plains, just north of the Banks Peninsula, the eroded remnant of the extinct Lyttelton Volcano, comprised of weathered basalt and Pleistocene loess [1]. The city was built on a historic floodplain of the Waimakiriri River, a large braided river that is now channelized approximately 25 km north of the CBD.

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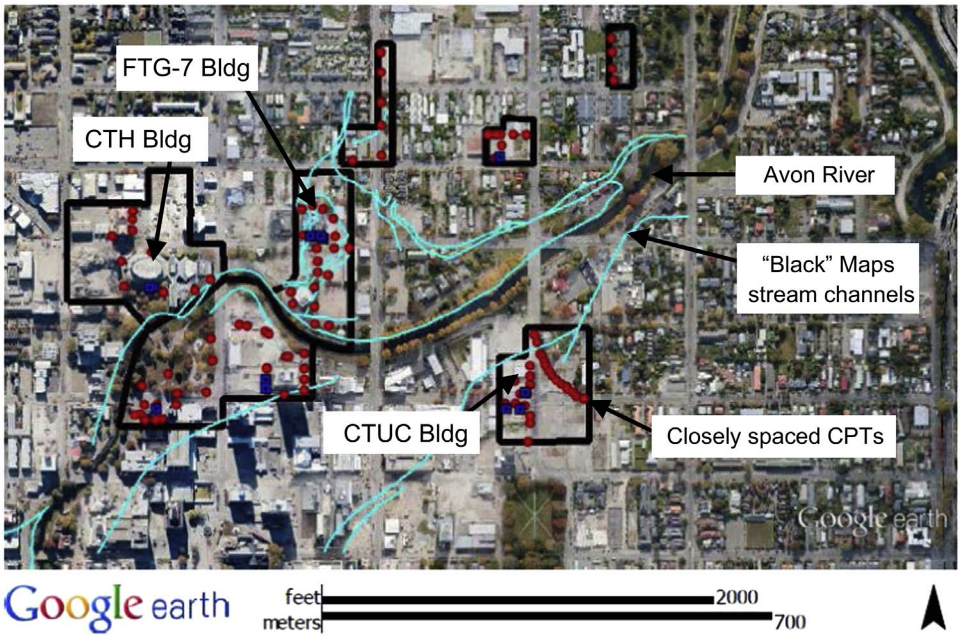

Fig. 1. UCB-UC CBD site investigation overview. CPTs are indicated with red dots, and boreholes are indicated with blue squares. Buried stream channels are from the 1850 "Black" Maps [1]. The locations of the FTG-7, CTH and CTUC building sites, and the closely spaced CPTs are labeled.

The Waimakiriri River regularly flooded Christchurch prior to the construction of levees and river realignment carried out shortly after the city was established in the 1850s [7,8]. The 1850 "Black" Maps depict several buried stream channels through the CBD, some of which are shown on Fig. 1 [1]. The subsurface conditions in the CBD are highly variable floodplain deposits with alternating layers of sands and gravels with overbank deposits of silty soils and some peat deposits..

There are three geological formations of primary interest in foundation engineering within the CBD: the Springston Formation, Christchurch Formation, and Riccarton Gravels. The Springston Formation was deposited during the last 3000 years and is the shallowest of the three formations. It consists of three lithologic units [7]: 1) gravels deposited in old flood channels of the Waimakariri River; 2) overbank alluvial silt and sandy silt; and 3) peat deposits formed in marshland. The Christchurch Formation consists of beach, estuarine, lagoon, dune, and coastal swamp deposits composed of gravel, sand, silt, clay, shells, and peat, and its top is found at a depth of typically 7–10 m within the CBD. It is a post-glacial deposit and likely less than 6500 years old near the maximum inland extent of the post-glacial marine transgression [7], which likely extended across the CBD based on the presence of shells observed in soil samples [9]. The Riccarton Gravels are beneath the Christchurch Formation and consist of well-graded brown or blue-grey gravels up to cobble size. This 10–20 m thick formation is the uppermost confined gravel aquifer in coastal northern Canterbury and is typically about 18–30 m below the ground surface in the CBD [7,9].

Two spring fed rivers, the Avon and Heathcote, meander through Christchurch and discharge into an estuary east of Christchurch. The Avon River, labeled in Fig. 1, meanders through the CBD, while the Heathcote River flows south of the CBD. Much of the observed moderate-to-severe liquefaction within and to the east of the CBD occurred near the Avon River during the Canterbury earthquakes. The groundwater table is generally within 1–3 m of the ground surface within the CBD.

Following the Christchurch earthquake, the Earthquake Commission of New Zealand (EQC) instigated a general subsurface investigation study of the CBD, which was organized by Tonkin & Taylor, Ltd. (T+T), that included 151 CPTs, 48 soil exploratory boreholes with index testing, 45 km of geophysical surveys, and installation of piezometers (New Zealand Geotechnical Database [10]). The UC Berkeley (UCB) – Univ. of Canterbury (UC) research team performed 107 CPTs and 13 exploratory boreholes, most of which are shown in Fig. 1, to characterize 23 building sites within six study zones. The structures in their study consisted of multi-story buildings on shallow and deep foundations and displayed interesting engineering performance characteristics.

A shallow layer of dense gravelly soils prevented the advancement of the conventional 10 cm^2 A.P. van den Berg cone with a 14 t CPT truck in several areas within the CBD (e.g., near Victoria Square). To overcome this issue, Mr. Iain Haycock of McMillan Drilling Services Ltd. (McMillan) developed a pre-collaring system to enable CPT profiling below dense gravelly soils layers [5]. The pre-collaring system was a steel dual tube system consisting of threaded steel outer casing with a nominal outer diameter (OD) of 69.9 mm and steel inner rods with a nominal OD of 31.8 mm (see Fig. 2a). At the base of the inner rod string was a conical steel tip that was designed to fit through the outer casing shoe. The dual tube assembly was then driven using a hydraulic hammer and direct push with a larger CPT truck with a self-weight of approximately 22 t. The CPTs that incorporated pre-collaring were performed as follows:

1) The cone was advanced per ASTM D5778-07 until refusal was encountered;
2) To advance to a greater depth, the CPT rods and probe were extracted from the hole;
3) Casing was then advanced using a hydraulic hammer in combination with direct push until the hydraulic ram gauge pressure was judged to be low enough to resume with a conventional cone;
4) The inner casing rods were extracted leaving only the outer casing rods in the hole;
5) The CPT cone and rod string was re-installed into the hole to the depth of the bottom of casing;
6) The CPT was resumed. If necessary, these steps were repeated.

The McMillan pre-collaring system generally had success in penetrating the dense gravelly soils of the type that caused premature refusal during the earlier attempts with the conventional CPT equipment. Representative CPT results from tests with and without the pre-