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Lateral spreading: Evidence and interpretation from the 2010–2011 Christchurch earthquakes

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ABSTRACT

In the 2010–2011 Canterbury earthquakes widespread liquefaction occurred over nearly half of the urban area of Christchurch. The most severe damage to buildings and infrastructure was often associated with lateral spreading and consequent large ground distortion and permanent ground displacements. This paper presents analysis, results and interpretation of lateral spreads using measurements from detailed ground surveying at a large number of locations along the Avon River. Classification of lateral spreads based on the magnitude and spatial distribution of permanent ground displacements is first presented, and then key characteristics of soil layers and ground conditions associated with different classes of lateral spreads are identified and discussed. Evidence of both global effects from topographic features and local effects related to density, thickness and continuity of critical layers is presented highlighting the need for a systematic approach in the engineering evaluation of lateral spreading in which particular attention is given to key factors governing lateral spreading.

1. Introduction

In the period between September 2010 and December 2011, Christchurch (population: ~380,000; area: ~450 km^2) was hit by a series of strong earthquakes known as the Canterbury Earthquake Sequence (CES). The sequence included four significant events with magnitudes M_w 5.9–7.1 and causative faults either in proximity to or within the city boundaries thus generating strong ground motions throughout Christchurch. The earthquakes caused tremendous damage to buildings and infrastructure, and total economic loss of approximately $30 billion dollars (NZD). The second earthquake in the sequence, the 22 February 2011 (Christchurch earthquake) was the most devastating; it caused 185 fatalities, mostly due to the collapse of two multi-storey reinforced concrete buildings.

The earthquakes had significant geotechnical aspects with ground failures and associated damage being widespread across the city and the most prominent damage feature outside the Central Business District (CBD). All four major events triggered extensive liquefaction particularly in the eastern suburbs of Christchurch. The Christchurch earthquake caused widespread liquefaction over nearly half of the city area while rock falls and slope instabilities affected residential areas in the Port Hills, along the south-east perimeter of the city. The extent of the liquefaction caused by the Christchurch earthquake is depicted in Fig. 1. The liquefaction affected nearly 60,000 residential properties and buildings (typically one-storey, and some two-storey, timber frame houses). Out of these, 20,000 properties were severely affected, and about 8000 properties were abandoned because the excessive damage caused by liquefaction and lateral spreading was deemed uneconomical for reinstatement of residential land [13]. Liquefaction and lateral spreading also caused heavy damage to CBD buildings, roads, bridges, and buried pipe networks of potable and wastewater systems of Christchurch. Examples of spreading-induced damage to buildings and infrastructure are shown in Fig. 2 with more detailed evidence presented in Cubrinovski et al. [7,8].

This paper focuses on lateral spreading, and presents results from a comprehensive study in which characteristics of lateral spreads were investigated in Christchurch using the so-called *ground surveying* method [11,16]. First, a large number of detailed measurements at locations affected by lateral spreading are used to identify magnitudes and distribution patterns of permanent ground displacements due to lateral spreading. Next, lateral spreads are classified based on their manifestation features, and then geotechnical analysis and interpretation are used to examine characteristics of soil layers and ground conditions in relation to different classes of lateral spreads. The key objective of this evaluation is to identify critical factors that influence and govern lateral spreading.

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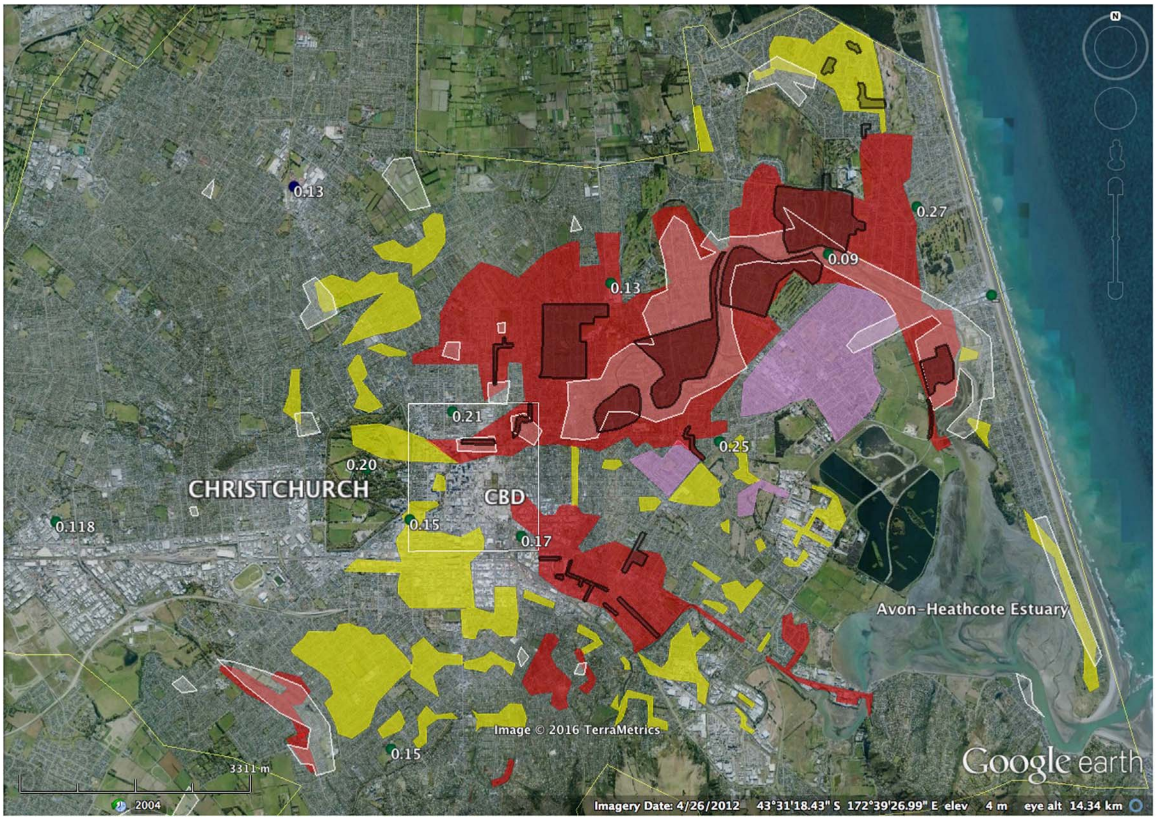

Fig. 1. Liquefaction maps indicating generalized areas of observed liquefaction in the 4 September 2010 (white contours), 22 February 2011 (red, yellow, magenta areas), and 13 June 2011 (black contours) earthquakes; cyclic stress ratios at the water table depth for reference magnitude M_w7.5, $CSR_{7.5(wt)}$, which were calculated using the recorded geometric mean peak ground accelerations and respective earthquake moment magnitudes are also shown; green symbols indicate strong motion stations (SMS) where the 22 February 2011 earthquake produced the highest $CSR_{7.5(wt)}$ values whereas the 4 September 2010 earthquake produced the highest $CSR_{7.5(wt)}$ values at the SMS shown with blue symbols. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Fig. 2. Spreading-induced damage to roads, residential buildings and CBD buildings in Christchurch.

2. Local geology and ground conditions

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. Originally, the site of Christchurch was mainly swamp lying behind beach dune sand, estuaries and lagoons, with gravel, sand, and silt of river channel and flood deposits of the coastal Waimakariri River flood plain [3]. The dominant features of present day Christchurch are the Avon and Heathcote Rivers, which originate from springs in western Christchurch, meander through the city and discharge in the Avon-Heathcote Estuary (Fig. 1).

Approximately 6500 years ago the coastline was near the western edge of the present-day CBD. The shallow subsurface in the eastern parts of Christchurch comprises of coastal swamp deposits of sands, silts, some clayey soils and peat (Christchurch Formation). In the western Christchurch, the Springston formation of alluvial gravels, sands and silts is prevalent. The water table to the east of the CBD is generally within 1.0 m to 1.5 m of the ground surface [5], and shallow soils within the top 10 m are less than 4,000 years old, and some are only few hundred years old, as depicted in Fig. 3 [6].

The depositional environment, soil composition, low in situ densities, young age of the deposits and shallow water table all point towards a high liquefaction potential of the shallow Christchurch soils, which was amply demonstrated during the Canterbury earthquakes.