Soil Dynamics and Earthquake Engineering 102 (2017) 99–111

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Seismic performance of a building affected by moderate liquefaction during the Christchurch earthquake

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ARTICLE INFO

Keywords:
Case history
Dynamic soil-structure interaction analysis
Liquefaction
Performance based earthquake engineering
Settlement
Shallow foundation

ABSTRACT

The seismic performance of an important structure in Christchurch, New Zealand was well-documented during the 2010–2011 Canterbury earthquake sequence. Minor ground deformation and negligible-to-minor structural damage occurred during the primary events of the sequence, except for the 22 February 2011 M_w6.2 Christchurch earthquake, which produced differential movement of the basement mat and architectural and structural damage. This case history is evaluated to garner insights. Static settlements are estimated to establish the pre-seismic conditions of the building. Dynamic nonlinear effective stress soil-structure-interaction analysis are performed for the primary events of the Canterbury earthquake sequence using FLAC2D with the PM4Sand constitutive model to capture the cyclic response of the key soil units. The analytical results indicate the post-Canterbury earthquake sequence measured differential mat movements were primarily due to the earthquake events. A thin liquefiable layer, which historic maps indicate is now a buried stream deposit, is largely responsible for the ground movements. A medium dense sandy gravel also appeared to contribute significantly to the observed foundation movements.

1. Introduction

Significant liquefaction-induced ground movements and building deformations were observed in several areas in the Central Business District (CBD) of Christchurch, New Zealand [1,2]. The comprehensive documentation of the seismic performance of an important building located in the CBD (herein referred to as Building C) during the 2010–2011 Canterbury earthquake sequence affords the opportunity to evaluate state-of-the-art nonlinear dynamic soil-structure-interaction (SSI) effective stress analytical procedures. The potential for liquefaction-induced ground movements to affect the building's performance is investigated.

After discussing liquefaction-induced building movements, the Building C case history is described in detail, which includes discussion of pre-seismic static settlement and earthquake-induced building movements. A recently recommended approach for evaluating liquefaction-induced building settlements is used and critiqued. Simplified liquefaction triggering and effects procedures are employed initially to gain insight. These analyses are followed by nonlinear dynamic SSI effective stress analyses. Analytical results are compared with field observations, and salient findings are presented.

2. Liquefaction-induced building movements

Liquefaction-induced building movements result from volumetric-induced deformation, shear-induced deformation, and loss of supporting ground due to the formation of sediment ejecta. Several publications discuss these phenomena [3–6]. Some of these mechanisms are shown in Fig. 1, which include: (a) ground loss due to soil ejecta; (b) shear-induced partial bearing capacity failure due to cyclic softening; (c) SSI shear-induced building ratcheting during earthquake loading; (d) volumetric strains due to sedimentation of the soil structure after liquefaction; and (e) post-liquefaction reconsolidation settlement. All of these mechanisms can contribute to the movement of a structure as a result of liquefaction in the soils beneath its foundation.

Post-liquefaction volumetric reconsolidation ground settlement calculations, such as those calculated using the Zhang et al. (2002) [7] procedure, only capture some of these mechanisms [3,4]. Liquefaction shear-induced displacements are not captured by simplified procedures that estimate only one-dimensional (1D), level ground, free-field, post-liquefaction volumetric settlements. Shear-induced building movements can be captured using advanced SSI numerical simulations with a soil constitutive model that can capture the cyclic response of liquefied soil as shown by Dashti and Bray (2013) [5], Luque and Bray (2015) [8], Bray et al. (2017) [9], and Karimi and Dashti (2016a,b) [10,11],

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http://dx.doi.org/10.1016/j.soildyn.2017.08.011
Received 1 October 2016; Received in revised form 23 June 2017; Accepted 23 August 2017
Available online 05 September 2017

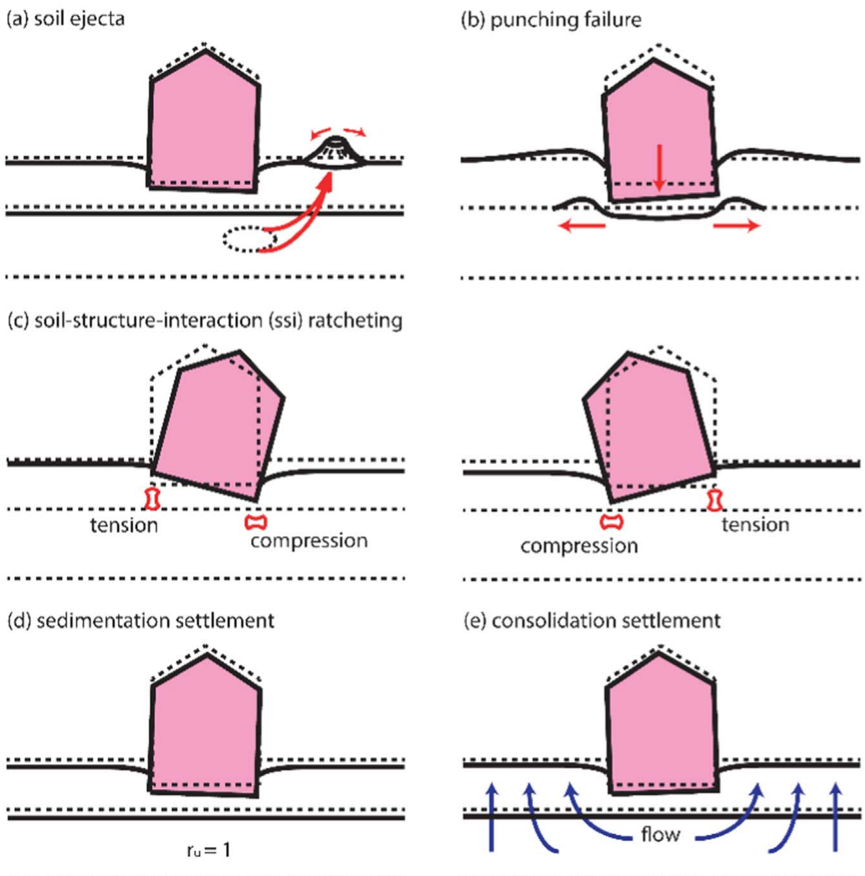

Fig. 1. Liquefaction-induced displacement mechanisms: (a) soil ejecta; (b) punching failure, (c) soil-structure-interaction (SSI) shear-induced ratcheting; (d) sedimentation and (e) consolidation (modified from Bray and Dashti 2014 [6]).

among others. Cetin et al. (2012) [12] and Unutmaz and Cetin (2012) [13] proposed a method to estimate the cyclic stress ratio (CSR) that included the inertial effects of the structure; settlement is calculated by integrating the estimated volumetric and shear strains. Karamitros et al. (2013a,b,c) [14–16] proposed a relationship for estimating liquefaction-induced building settlement as a function of the maximum ground surface acceleration, period of the ground motion, number of cycles, thickness of liquefiable layer, width of the building, and a degraded factor of safety. Bertalot et al. (2013, 2015) [17,18] concluded that high bearing pressures and high initial static shear stresses prevent stress reversal, which limits pore water pressure generation and building settlement. There are not quantitative methods for evaluating the potential effects of sediment ejecta at a building site, so engineering judgment must be exercised when considering this mechanism [9].

3. Building C case history description

3.1. Structural configuration

Building C is a 2-story structure built partially atop a one-level basement parking structure that occupies a site in Central Christchurch [19]. The basement measures 69 m in the EW direction and 82 m in the NS direction (Fig. 2). The 0.4-m thick perimeter basement wall is built of reinforced concrete (RC). The basement foundation is a combination of a 0.5-m thick RC mat in the SW corner and 0.4-m thick RC mat in the remainder of the basement. RC spread footings of varying dimensions directly underlie the mat below interior columns that support the ground floor. Irregularities exist in the North side of the basement where stairs and elevators are located. The design elevation of the basement floor is variable with the SW corner being around 0.6 m lower than the remainder of the basement. The ground floor is a combination of a 0.4-m thick "unispan/concrete" slab and a 0.6-m thick in-situ concrete slab. The basement columns are connected with beams of variable sizes at the ground floor level in the NS direction.

Anchor piles (0.3 m in diameter) are installed in the SW area of the basement to prevent uplift of the building due to a high water table. Anchor piles are also installed in some of the foundation pads located in its NE corner to resist uplift forces during earthquake shaking. Aurecon (2012) [20] reports the number of anchors installed and the volume of grout required to install the anchors in the SW area were more than anticipated. Their assessment indicates grout infiltrated permeable layers and densified loose layers, which reduced their liquefaction potential.

Two almost separate structures, herein called C-N (North) and C-S (South) buildings, are supported on the east side of the basement (Figs. 2 and 3). The C-S building is 30 m by 38 m in the NS and EW directions, respectively, and 14.2 m high above the ground level. The C-N building is 48 m by 31.5 m in the NS and EW directions, respectively, and 15.7 m high above the ground level. The C-S building's eastern perimeter extends 6.5 m beyond the basement wall. The two buildings are connected along their eastern sides. Both structures consist of precast RC shear walls in the perimeters and interior RC columns and beams. The floors of both buildings consists of combinations of precast RC floors; either 0.6 m-thick precast pre-stressed RC double tees with 0.1-m thick concrete topping or 0.2-m thick hollow core floor units with 0.075 m topping.

3.2. Subsurface conditions

The subsurface conditions at Building C have been characterized by several entities at different times using in-situ tests that include soil exploratory boreholes with the Standard Penetration Test (SPT), cone penetration testing (CPT), and Multi-Channel Analysis of Surface Waves (MASW) as shown in Fig. 2. Soil density was evaluated primarily with