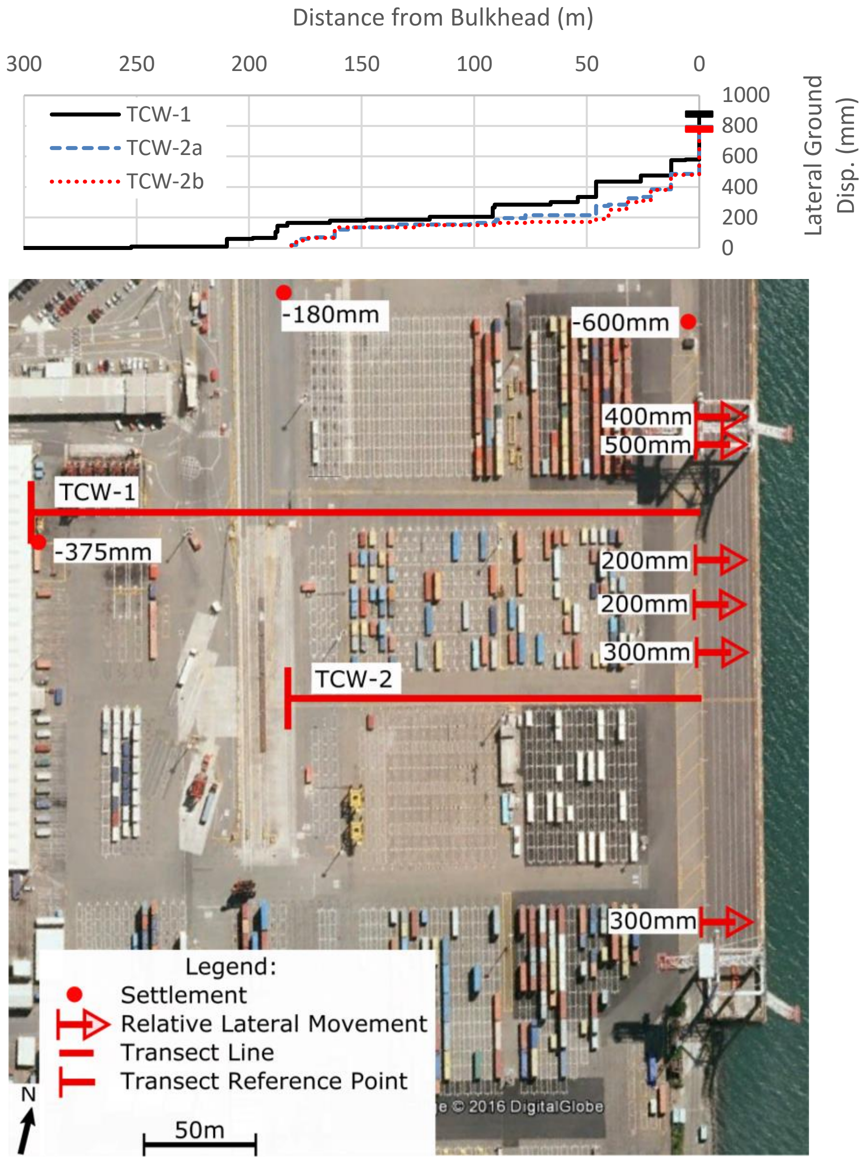


Figure 15: Location of west-to-east transects for lateral spreading measurements towards Thorndon Wharf during inspections. Plots at the top show cumulative lateral ground displacement versus horizontal distance from the bulkhead (Base image from Google Earth™).

LIDAR FIELD SURVEY

Ground-based LiDAR surveys were completed at CentrePort from 28 November to 1 December 2016 to document the ground and structural performance during the 2016 Kaikoura earthquake. The LiDAR surveys were collected to supplement and validate structure from motion (SfM) point clouds from recent unmanned aerial vehicle (UAV) surveys.

The surveys were completed using a Leica P40 terrestrial laser scanner with a Leica GS14 GNSS receiver mounted above at a calibrated offset of 0.1580 m. Scans were spaced generally at 30-40 m apart along transects (Figure 16); however, the spacing varies substantially to accommodate visibility constraints as well as safety considerations since the port was operational during the surveys. Scans were completed for a 360 degree panoramic view. Most scans also have co-acquired, high resolution imagery utilizing the internal calibrated camera in the Leica P40 scanner. At each location where imagery were collected, the camera captured over 270 (1920x1920) images for the full dome, which were mosaicked and blended together to map colours to the point cloud. For some of the indoor scans with poor lighting conditions or where scans needed to be completed rapidly, the camera imagery was not acquired. For indoor scans, the GNSS receiver and handle were removed prior to scanning, in most cases, for full overhead scanning. A local Continually Operating Reference Station (CORS) WGTT was utilized as the base station. Details on the LiDAR surveying including GNSS processing, registration, and DEM creation are provided in [1].

Figure 17 shows a cross-section (LT1) extracted from the LiDAR data that was obtained on the west edge of the road immediately west of Building S37. The peaks in this plot indicate locations of the buried piles whereas the lower portions show the magnitude of settlement of the pavement surface around those piles. In absence of detailed survey data prior to the event, the original surface was estimated by fitting a 3rd order polynomial ($R^2 = 0.99$) to the tops of piles showing higher elevations in the local area. Using this assumption, a differential settlement of the ground (settlement of the ground relative to the ground surface covering the tops of the piles) in this area was estimated to be on the order of 200 mm to 300 mm. LiDAR surveying data on the performance of wharves and buildings are presented in the subsequent sections.

Figure 16: Locations (green circles) where ground-based LiDAR scans were obtained at the CentrePort. Additional scans were captured inside the Cruise Ship Terminal to the North that are not shown. Transects from the LiDAR data shown later in the report are identified. Note that the basemap is from ESRI prior to the earthquake.

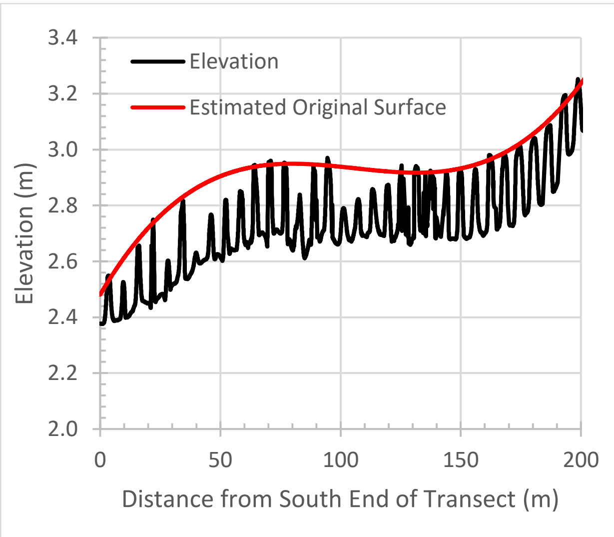


Figure 17: Post-earthquake elevations for transect (LT1) along west side of roadway west of S37; the red line represents the estimated pre-elevation surface.

EFFECTS ON WHARVES

CentrePort Wellington has two wharves: Thorndon Container Wharf and King's Wharf (see Figure 18). The port's primary container operation takes place on Thorndon Container Wharf, which is on the eastern side of the port. King's Wharf, which is on the western side of the port, supports primarily roll-on/roll-off cargo.

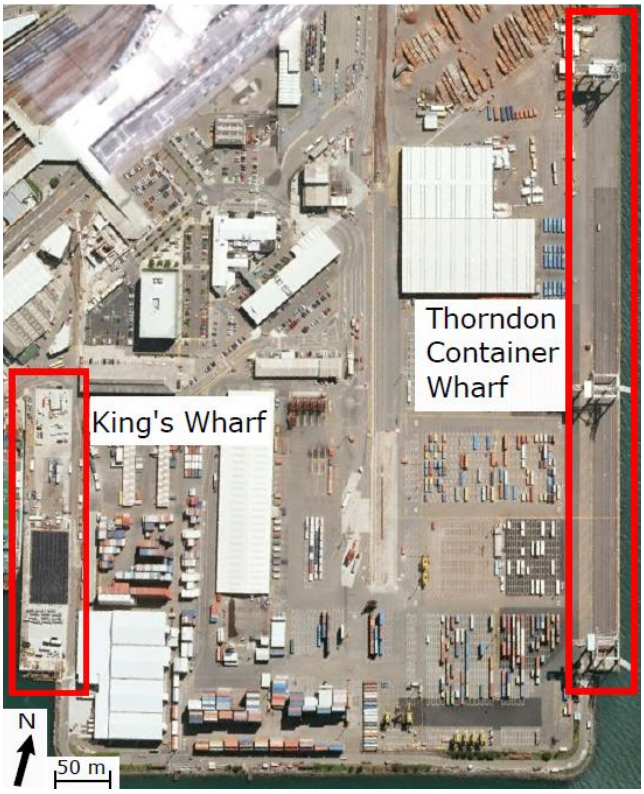


Figure 18: Aerial photograph highlighting the locations of the Thorndon Container and King's wharves of CentrePort Wellington (Base image from Google Earth™)

Thorndon Container Wharf

The Thorndon Container Wharf is supported on seven rows of 508x508-mm square, pre-stressed concrete piles. Pile bents are spaced 3.66 m on center (approximately s = 6B). The piles are generally 18 m long under the eastern crane rail and 20 to 23 m long (increasing in length to the south) under the western crane rail [4].

As described previously, widespread liquefaction of the Thorndon Reclamation was accompanied with settlement of the fill and lateral spreading towards Thorndon Wharf. Ground survey measurements indicate that the lateral spreading displacements at the edge of the fill (bulkhead) reached about 0.8 m to 1.0 m, relative to the respective reference points. Cardno performed an aerial unmanned aircraft systems (UAS) survey of the port that captured vertical settlement and lateral movement (Figure 19). The magnitude of lateral spreading displacement and ground settlement from the UAS survey are generally consistent with those measured by the QuakeCoRE-GEER team [1].

The lateral thrust from the displaced fill pushed the inland piles of the wharf towards the sea, causing tilt of the wharf. The crane rail tilted 2.5° down towards the sea at TWC-1 and 1° down towards the sea at TWC-2 (see Figure 15 for transect locations). Lateral seaward movement measurements of the bulkhead relative to the ground immediately inland range from 200 to 500 mm. These estimates are based on surface observations of asphalt cover movement, which do not necessarily represent movement of the underlying soil beneath the asphalt. In fact, at this interface zone of large horizontal and vertical offsets between the fill and wharf, cavities were apparent immediately below the distorted asphalt cover. Figure 20 shows the vertical offset created between the pile-supported wharf and reclaimed fill behind the wharf. Deformation of the Thorndon Wharf was also captured in the LiDAR survey (see Figure 21).

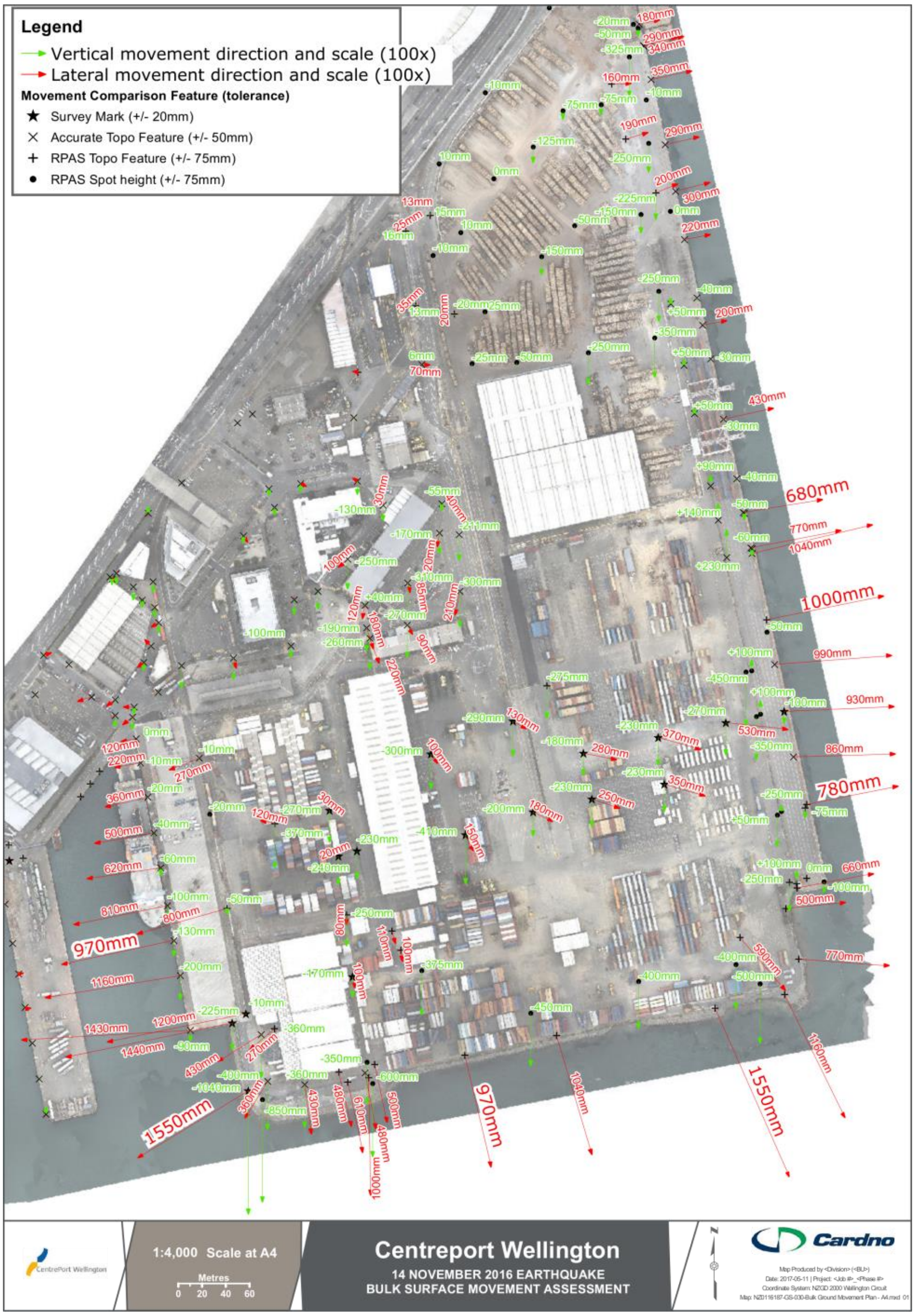
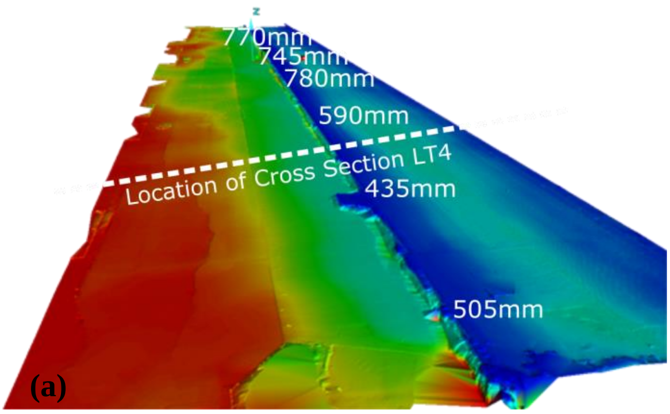


Figure 19: Displacements measured from an aerial UAS survey of Thorndon Reclamation and Wharf (performed by Cardno).

Figure 20: (a) Looking south along Thorndon Wharf bulkhead at approximately STA 240. Approximately 600 mm of ground settlement was measured relative to pile-supported wharf. (S41.278250° E174.789205°, taken at 1124 hrs on 21NOV16); and (b) Looking north along Thorndon Wharf bulkhead at approximately STA 280. Approximately 600 mm of ground settlement was measured relative to pile-supported wharf. (S41.277743° E174.789236°, taken on 22NOV16).



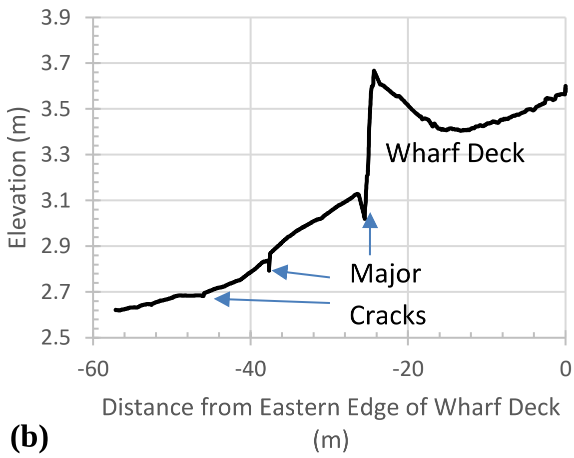


Figure 21: (a) Perspective view of the LiDAR DEM of the eastern section of the port looking northward including the Thorndon Wharf and surrounding fill area coloured by elevation to highlight discontinuities from cracks. Elevation ranges from approximately 2.60 m (red) to 3.60 m (dark blue). Differential settlements between the wharf and reclaimed land are identified. (b) Elevation profile for cross section LT4 across Thorndon Wharf and inland fill.

The QuakeCoRE-GEER team was informed that concrete piles had been sheared near the pile cap (from a boat survey by others; T+T (2016) private communication). From the south side of the port, the team did observe a vertical bulkhead pile sheared just below the pile cap.

King's Wharf

King's Wharf is supported on driven timber piles. The fill behind the wharf liquefied and moved laterally towards the wharf displacing King's Wharf seaward (to the west). Spreading displacements were largest at the south end of the wharf where the lateral soil movement exceeded 1.1 m, based on ground surveying measurements. The ground along the edge of the reclamation displaced westward (towards the wharf) and collapsed downwards (beneath the wharf deck). The ground settlement relative to the deck of the wharf was measured with hand surveys to be approximately 560 mm at the southeast corner of the wharf and 530 mm at the northwest corner of the CS building, which is described later.

Westward movement of the structure is visible in Figure 22a, in which the southern bent of piles leans to the west. The inland timber piles split due to seaward lateral movement of the deck relative to this row of piles (Fig. 22b). Vertical warping of the wharf deck is shown in the LiDAR DEM (Fig. 23a). The wharf deck exhibits significant concavity (downward) as observed in the cross section plotted on Figure 23b. Differential settlement between the wharf and adjacent ground range from 475 mm to 630 mm, as measured from the LiDAR-derived DEM.

EFFECTS ON BUILDINGS

General

Several engineered buildings located on or adjacent to CentrePort were affected by the liquefaction-induced ground movements at the port. Most buildings were supported on pile foundations. A few buildings were supported on shallow foundations. Observations for each building identified in Figure 24 are presented in the following sections.

Figure 22: (a) Looking west along southern end of King's Wharf showing westward tilt of piles (S41.281281° W174.784097°, taken on 17NOV16), and (b) looking under King's Wharf at an inland bulkhead pile; timber pile is split from lateral movement of the deck relative to the pile. (S41.280900° E174.784375°, taken on 21NOV16).

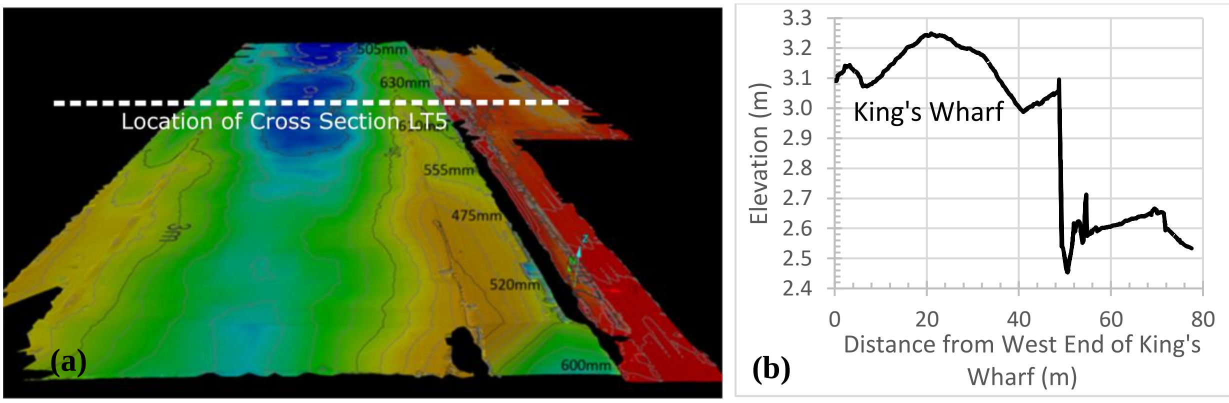


Figure 23: (a) LiDAR derived DEM (looking northward) of the pile-supported King's Wharf showing measurements of differential settlement between the wharf and the adjacent ground. Elevation ranges from approximately 2.50 m (red) to 3.30 m (dark blue). (b) Cross section LT5 taken across King's Wharf and the adjacent ground.

Buildings on Shallow Foundations

CPH Building

The CPH building (S41.27829° E174.78618°, see Figure 24) is founded on reinforced concrete (RC) spread footings connected with RC grade beams (Figure 25a). There were no apparent signs of structural distress, and the building was operational at the time of the reconnaissance in late November 2016. The building and immediately surrounding fill settled relatively uniformly. Settlement appeared to be more or less uniform across the building footprint, as there were no apparent signs of relative movement or tilt of the ground floor of the CPH building from the visual investigation. However, a preliminary analysis of the LiDAR scans indicate a slight tilt (i.e., of 0.105 degrees) in the large operations room on the east end of the building. Ground a few meters to the west of the CPH building did not appear to settle significantly, because it was supported by the buried precast seawall that ran along the bulkhead of the partially demolished Pipitea Wharf, which minimized liquefaction-induced settlement of the ground above it. The building and fill settled approximately 230 to 260 mm relative to the elevated ground supported on the seawall (Figure 25b).

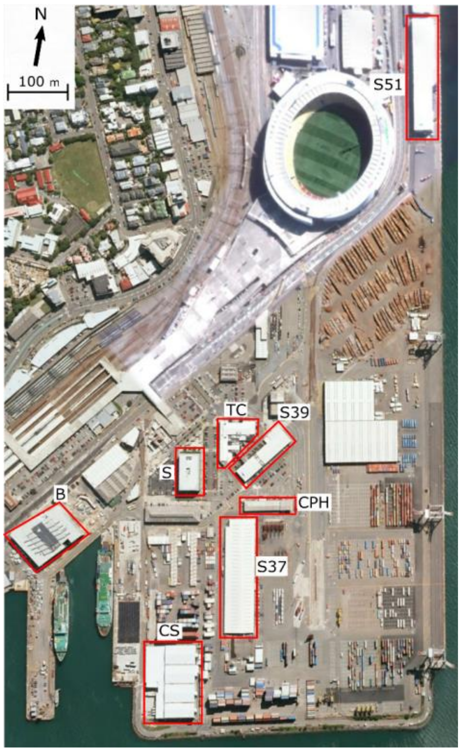


Figure 24: CentrePort Wellington map showing buildings surveyed (Base image from Google Earth™).

Figure 25: (a) Uniform settlement of CPH building which is founded on shallow foundations that apparently displaced downward the same amount as the surrounding fill. This photo is looking northeast at the southwest corner of the building. (S41.278395° E174.785639°, taken on 21NOV16). (b) Uniform settlement (230-260 mm) of the building relative to ground supported on the buried precast seawall that ran parallel to the bulkhead of partially demolished Pipitea Wharf. Looking north along western wall of CPH building. The perimeter walkway slopes down towards the building at 11 degrees over 1.35 meters. (S41.278395° E174.785639°, taken on 22NOV16).

CS Building

The CS building (S41.28105° E174.78483°, see Figure 24) is supported on a composite shallow foundation with RC spread footings and mats. The building consists of an irregular-shaped single-story open loading bay in its western part (herein called the Shed) and a rectangular-shaped large cold storage facility on its eastern part (herein called the Freezers). The structural frames and supporting foundations of these two parts of the building appear to be independent. From observation, the structural system of the Shed is composed of concentrically-braced steel frames. The QuakeCoRE-GEER team members were given access to the Shed and the ground around the building, but not to the Freezers. The differential ground movements across the building footprint induced structural deformation in the CS building. Seaward lateral ground movements on the order of 1 m occurred towards the western and southern slopes in the southwest corner of the CentrePort reclaimed land.

Figure 26 shows the location of six transects along which the location and width of lateral ground cracks in the pavement surrounding the CS building were recorded. Superimposed on this figure are plots of cumulative lateral ground displacement as a function of distance from the crest of the waterfront slopes for each transect. They show the fill moved towards the sea (southward) approximately 0.8 to 1.3 m (relative to the reference point of measurement), at the south side of the building. The fill moved 0.8 to 1.1 m to the west. The foundations of the building were subjected to a lateral stretch of approximately 200 mm over a column span of approximately 8.8 m. This corresponds to a lateral strain of about 2.3%.

Gravelly liquefaction ejecta was observed around the building. Figure 27a shows lateral ground movements and partial collapse of the slope at the reclamation edge along the western wall of the Shed of the CS building (which is parallel and adjacent to King's Wharf), where the ground settled approximately 530 mm relative to the King's Wharf. This part of the building is closest to the crest of the slope and it underwent the largest lateral movement. Figure 27b shows lateral movements near the crest of the western slope, and Figure 27c shows lateral spreading towards the southern slope with a consequent vertical offset of approximately 1.1 m. Significant separation between the CS building foundation and external pavement slab were observed on the south side of the building (as well as settlement and spreading of the surrounding pavement). Shallow soils beneath the pavement were exposed in large cracks and vertical offsets surrounding the building, and these soils consist of gravelly quarry-rock reclamation fill.

Figure 28a documents significant cracking resulting in exposure of rebar in the foundation of the CS building along the exterior northern wall. The photograph looks south at the north wall of the CS building, however, this same ground crack runs northward continuously for approximately 100 m. Crack widths and locations along the bottom of the outside walls of the CS building were also measured. Figure 29 shows results of this survey, which are consistent with the previously described lateral spreading measurements and also indicate a lateral stretch of the shallow foundation of the Shed of approximately 200 mm in the westward direction along the northern wall.

The western part of the CS building (i.e., the Shed) is a steel-frame, single-story structure with an open bay. The total span of the Shed on its north end is about twice as wide as its span width on its south end. The northwest part of the Shed is closest to the free-face of the slope and consequently experienced the largest lateral ground movement. Thus, the northern part of the Shed displaced laterally westward more than its southern end. The westward lateral movement of the north end of the building separated the Shed from the Freezers along the northern half of the building (Figure 28b). The differential lateral ground movements across the north-south length of the Shed produced deformations, cracks, and openings in the overlying foundation and structure. This deformation pattern was apparent by comparing the magnitude of building cracks along the north wall to those on the south wall (Figure 29), as well as separation of construction joints in the interior floating slab of the Shed. Measurements of construction joint separation in the slab are shown schematically in Figures 30 for the southern part of the Shed. The differential lateral ground movements across the footprint of the Shed part of the CS building were also manifested in the deformation pattern of its steel framing. This deformation pattern is shown in Figure 31, which is a schematic of the three west-most columns of the four column frame along the north wall looking north from the interior. The column span is approximately 8.7 m. In addition to the tilting of these columns along the north wall, at least two columns along the east wall of the shed were rotated at the base, causing buckling of the concentric bracing between columns (Figure 32).

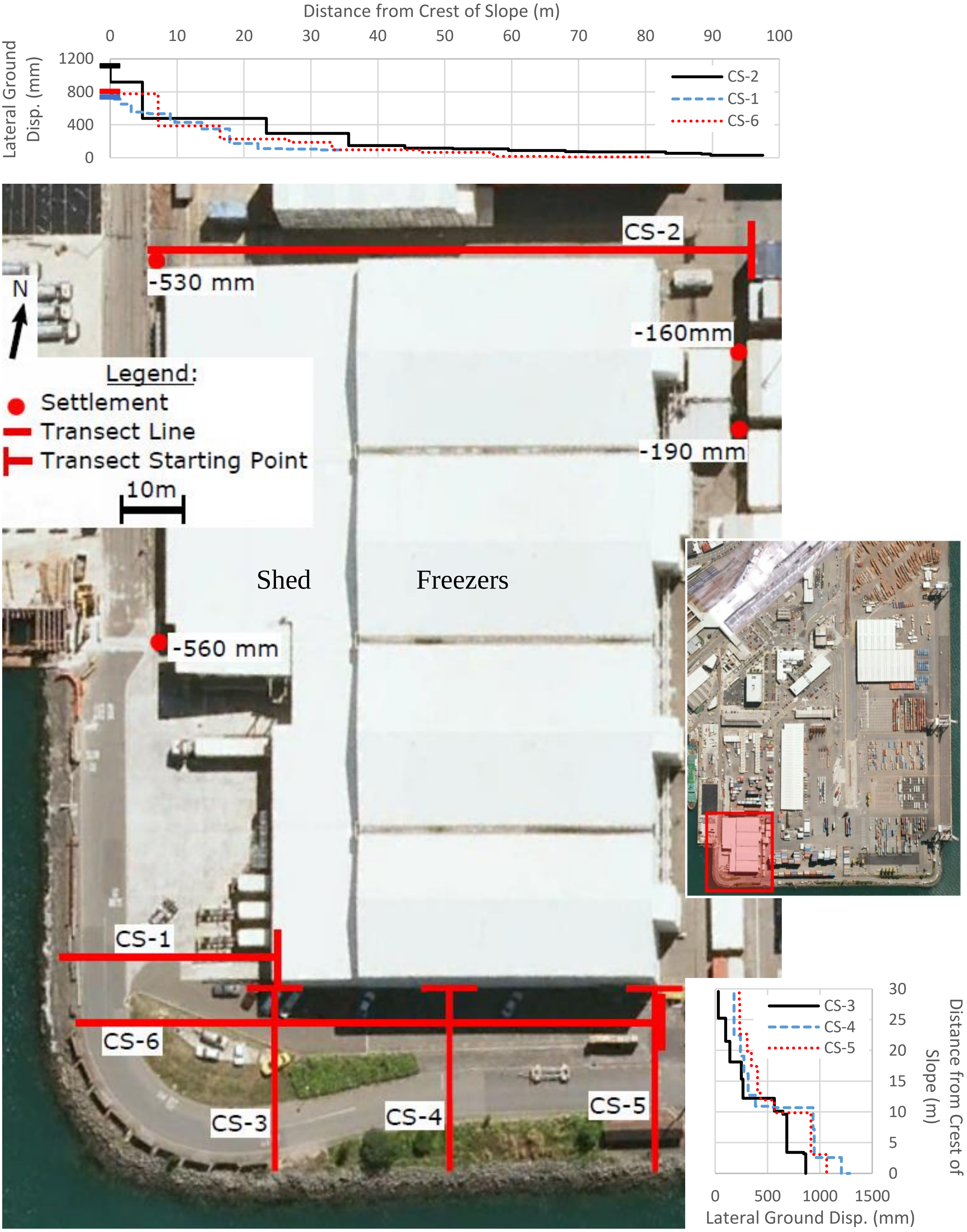


Figure 26: CS building lateral ground movement transects and vertical settlement measurement locations. Cumulative ground displacement versus distance from crest of slope are provided in the inset plots. Note that the crest of slope is further east at CS-2 than at CS-1 and CS-6, therefore, displacement plots do not perfectly align with satellite image for CS-2. Settlement measurements to the northeast are relative to the building which also settled.

Figure 27: (a) Looking north along the west wall of the CS building. The ground settled approximately 530 mm relative to the pile-supported bulkhead of King's Wharf, which is shown at the left side of the photograph. (S41.280923° E174.784389°, 21NOV16); (b) Ground cracks in area west of the CS building and along the southwestern slopes of CentrePort (looking south). The CS building can be partially seen on the upper left corner of the photograph. (S41.281478° E174.784430°, 21NOV16); and (c) Approximately 1.1 m of vertical offset resulting from the southward lateral movement of the southern edge of CentrePort reclaimed land near its western side. Looking west near the southern wall of the CS building. (S41.281701° E174.785268°, 21NOV16).

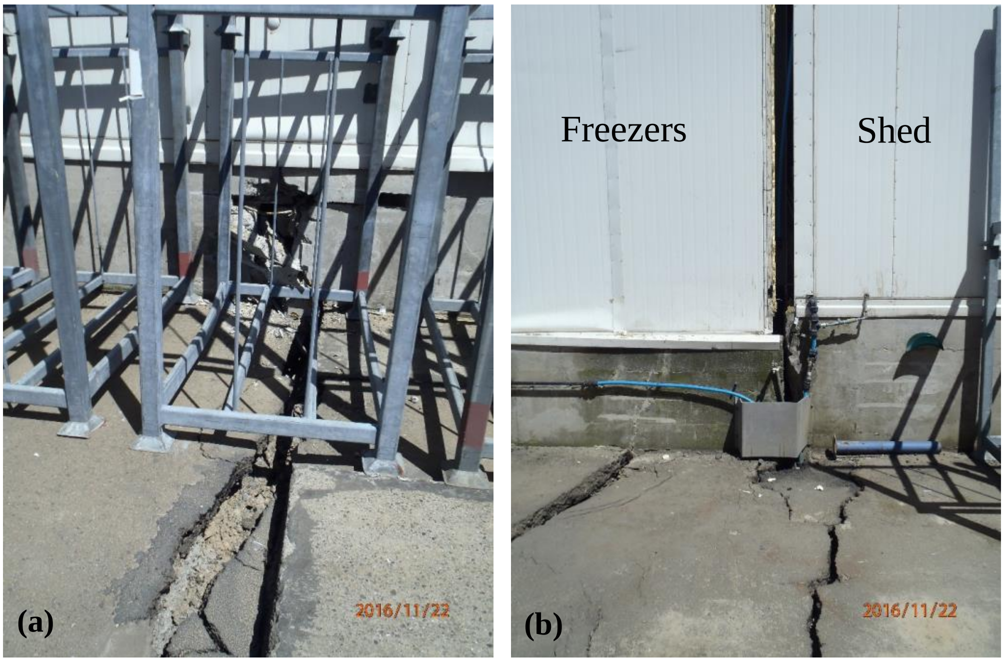


Figure 28: Cracks along the exterior north wall of CS building: (a) 180 mm crack in the foundation of the CS shed from westward lateral spreading (S41.280607° E174.784533°, 22NOV16), and (b) 150 mm of separation between Shed and Freezers (i.e., westward/seaward movement of the Shed relative to the Freezers), (S41.280584° E174.784705°, 22NOV16).

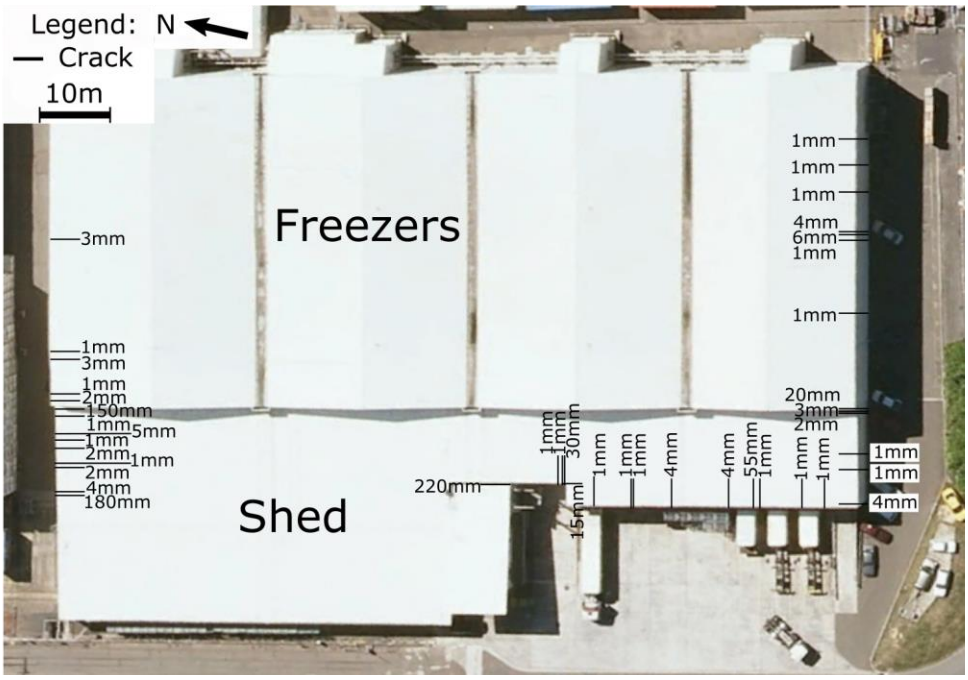


Figure 29: Location and width of lateral ground movement-induced cracks in the RC concrete walls at the base of the exterior building walls of the CS building. Crack openings are parallel to the respective wall.

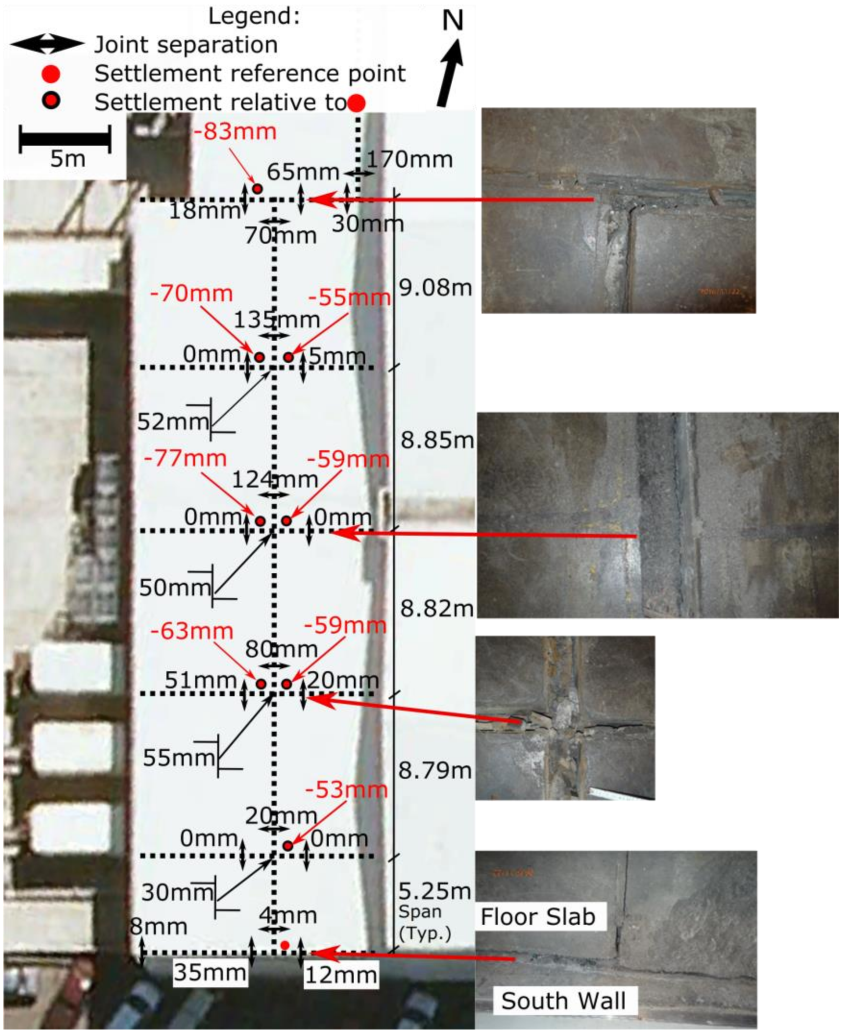


Figure 30: Southern part of Shed floor slab construction joint separation measurements. Photographs along right side of figure are of construction joints at which measurements were taken and are aligned vertically with each depicted joint. (Surveyed 22NOV16).

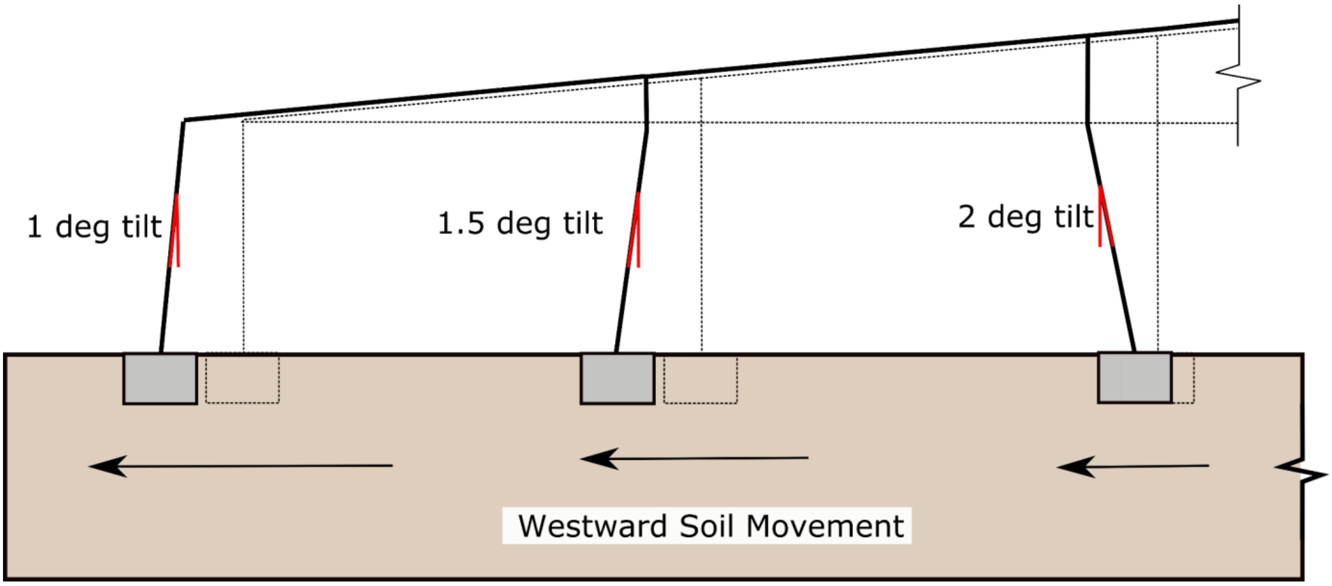


Figure 31: Schematic of deformation pattern of steel frame along the north wall of CS building (three west-most columns of the Shed; looking north from interior).

Figure 32: Internal east wall in northern part of the Shed, which shows column-pedestal connection failure due to rotation of the base of the column and buckling of concentric bracing. (Approx. at S41.280939° E174.784778°, 22NOV16).

Buildings on Deep Foundations

S39 Building

The S39 building (see Figure 24) is supported on Frankie piles. The old buried mass concrete seawall (i.e., Old Seawall) runs parallel and adjacent to the southeast wall of the building. Additionally, along the southeast wall, a segment of the historic Fryatt Quay Wharf deck (Figure 3) was left intact. The ground to the south of the seawall and wharf settled 220 mm relative to the top of the wharf deck and the pile-supported building (Fig. 33a). Approximately 100 to 190 mm of settlement was observed along the southwest wall of the building (Figure 33b). On the northwest side of the building, the ground adjacent the building settled approximately 50-100 mm relative to the building. The QuakeCoRE-GEER team was informed that the ground floor slab dropped 150 mm inside the building (T+T (2016), private communication).

TC Building

The TC building (see Figure 24) is immediately to the northwest of the S39 building, and is supported on driven RC piles. Liquefaction ejecta was observed along the short southwest wall of the building, and 150 mm of ground settlement relative to the building was measured.

Figure 33: (a) Southeast side of Building S39 and a buried segment of the Fryatt Quay Wharf deck parallel to the building. Fill to the south of the buried mass concrete seawall/wharf settled 220 mm relative to the pile-supported building and wharf deck. (S41.277984° E174.785776°, 22NOV16), and (b) looking southeast along southwest wall of Building S39. Fill settled approximately 190 mm relative to pile-supported building at the northwest corner of the building (shown on lower left corner of photo), and magnitude of settlement decreased south-eastward along this wall. (S41.277994° E174.785467°, 17NOV16).

S37 Building

The western half of the S37 building (see Figure 24) is founded on the deck of the buried, partially demolished pile-supported Pipitea Wharf, and the east wall of the building is supported on piles. The precast seawall that formerly ran along the bulkhead of the Pipitea Wharf is now buried and runs south-to-north through about the centerline of the building. The ground floor slab not supported on piles, the old wharf deck, or the precast seawall settled up to 550 mm relative to these structures (Fig 34a; the value is based on measurement from LiDAR scan for this building). The ground settled approximately 375 mm relative to the building along the exterior of the east wall of the S37 building (Figure 34b). Approximately 16 m west of the western wall of the S37 building, a buried row of piles from the old Pipitea Wharf protruded from the ground as the surrounding fill settled approximately 300 mm relative to the piles (Figure 17).

S51 Building

The S51 building (see Figure 24) is in the northeastern reclaimed land of CentrePort, which is an area reclaimed using hydraulically-placed dredged fill.

Figure 34: (a) Looking west across north wall of Building S37. Approximately 400mm of differential settlement between ground and deck of buried, pile-supported Pipitea Wharf that supports the western side of the shed. (S41.278571° E174.785632°, 21NOV16); and (b) looking south along east wall of Building S37, which shows approximately 375 mm of differential settlement between fill and pile-supported east wall of the building. (S41.279065° E174.785787°, 21NOV16).

The eastern wall of the building is founded on the pile-supported wharf, and the remainder of the building is founded on piles. The ground south of the building settled 230 mm relative to the wharf deck. Settlement magnitudes decreased from south to north, and only 10 to 20 mm of ground settlement was observed relative to the wharf in the surrounding ground north of the building. At the southern end of the building, the wharf that supports the eastern wall moved laterally eastward approximately 85 mm (35 mm crack at bulkhead and 50 mm crack 14.6 m west of bulkhead), which resulted in cracking of the southern wall near the wharf bulkhead. This equates to 85 mm of lateral movement over 14.6 m corresponding to a lateral strain of approximately 0.58%. Additionally, several vertical cracks were observed in the western exterior walls of the building.

S Building

The S building (see Figure 24) is a 5-storey reinforced concrete building founded on piles, which was built in 2006. The corners are on driven reinforced concrete piles while the interior columns are founded on cast-in-place concrete piles. No ground improvement was performed under the building. The building suffered structural damage, and is being investigated thoroughly by CentrePort. No signs of foundation damage were visible at the ground surface during the QuakeCoRE-GEER team visit though some level of distress in the ground adjacent to the building was evident. The ground settled 100 to 200 mm relative to the pile-supported building (Figure 35), in a relatively uniform fashion though some deviations from this pattern were also evident. Ground floor infill walls along the perimeter of the building were cracked in places, and the Level 1 floor slab pulled out and partially collapsed.

Figure 35: Looking west at southeast corner of the S building at which fill settled approximately 100 to 200 mm relative to pile-supported building. (S41.278285° E174.784757°, 21NOV16).

B Building

The B building (see Figure 24) is supported on piles with stone column ground improvement performed over the southeastern (seaward) half of the building footprint. The surrounding ground settled approximately 50 to 90 mm uniformly relative to the building (Figure 36). No other significant movements were observed.

CONCLUSIONS

Widespread liquefaction occurred in the end-dumped gravelly fills and hydraulically placed dredged sandy fills at the CentrePort of Wellington as a result of the 2016 Kaikoura earthquake. The liquefaction manifestation varied from traces of ejected soil and water on the pavement surface to larger volumes of ejecta with thicknesses of up to 150-200 mm. The ejecta south of the Old Seawall consisted predominantly of gravelly soils including some cobble-size particles. The reclamation south of the Old Seawall was largely end-dumped gravelly fills. However, there were areas of sandy ejecta south of the Old Seawall. Sand ejecta were found largely north of the Old Seawall in the hydraulically placed sandy fills.

The liquefaction resulted in a substantial global (mass) settlement of the reclamation and lateral spreading towards the sea, which adversely affected wharf structures and buildings constructed on shallow and deep foundations. The settlement of the fill south of the Old Seawall was generally in the range from 200 mm to 500 mm, while permanent lateral spreading displacements at the edges of the reclamation either reached or exceeded 1.0 m.

Liquefaction-induced ground deformations and spreading caused the wharves to displace laterally and tilt-down towards the sea, and the wharf movements damaged their piles. In the zone affected by spreading, lateral ground extension and differential settlement damaged the CS building on shallow foundations. Buildings in areas of liquefaction-induced settlement without lateral extension performed significantly better. Buildings on shallow foundations settled more or less uniformly though some relative soil-foundation movements and ground distress were apparent along the perimeter of the building, whereas ground adjacent to pile-supported buildings settled typically in the range from about 100 mm to about 500 mm relative to the building.

ACKNOWLEDGEMENTS

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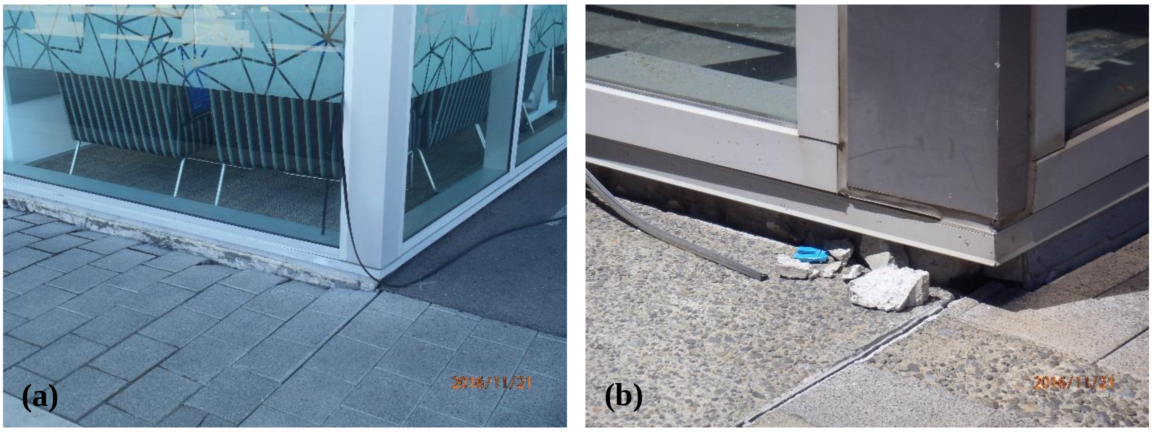

Figure 36: Ground settlement relative to the pile-supported B building at: (a) the southwest corner of the building with ground improvement (S41.279767° E174.782100°, 21NOV16), and (b) northwest corner of the building without ground improvement (S41.279419° E174.781443°, 21NOV16).

The NZ-US QuakeCoRE-GEER team performed on-site reconnaissance on November 17, 20, 21, 22, 23 and 30, and December 1 and 2, 2016. Profs. Misko Cubrinovski, University of Canterbury, and Jonathan Bray, University of California, Berkeley, led these QuakeCoRE-GEER efforts and participated in the inspections on multiple occasions. Christopher de la Torre (UC) contributed to most of these inspections and compilation of the gathered data. Prof. Brendon Bradley (UC), Dr. Gabriele Chiaro (UC) and Dr. Liam Wotherspoon (UA) also were members of the early reconnaissance teams. All LiDAR scanning at CentrePort was performed and processed by Prof. Michael Olsen, a U.S. GEER team member from Oregon State University, with his student, Matthew O'Banion. Leica Geosystems, David Evans and Associates, and Maptek I-Site provided equipment and/or software utilized in this study. Particle-size analyses on the ejected soils were performed in the Geotechnical Laboratory of the University of Canterbury. This is QuakeCoRE publication number 0168.

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