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GROUND PERFORMANCE IN WELLINGTON WATERFRONT AREA FOLLOWING THE 2016 KAIKŌURA EARTHQUAKE

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ABSTRACT

Although located about 200 km away from the epicentre of the 2016 Kaikōura Earthquake, the waterfront areas of Wellington City suffered varying degrees of damage as a result of soil liquefaction and associated ground deformations. This paper presents a summary of the major observations made following reconnaissance inspections of the geotechnical effects caused by the earthquake, with emphasis on the ground performance in the affected areas near the waterfront. Except for CentrePort, summarised elsewhere in this Special Issue, the inspections concentrated mostly on the waterfront areas and the impact to buildings built on reclaimed lands. Cracks and minor ground subsidence were observed in many parts of the waterfront, but the damage was less than that in CentrePort where significant liquefaction-induced damage was evident. The age of reclamation appears to have significant effect on the distribution of liquefaction-induced damage, while reclaimed areas where improvement techniques have been implemented performed well.

INTRODUCTION

The M_w7.8 Kaikōura Earthquake, which struck the northern part of South Island just after midnight of 14 November 2016, caused significant ground damage not only to the hilly areas in the vicinity of the epicentre, but also in some parts of the southern region of North Island. Although located more than 200 km away from the epicentre, the waterfront areas of Wellington City suffered varying degrees of damage as a result of soil liquefaction and associated ground deformations. Pavement cracks, ground fissures, differential settlements and subsidence were observed in many parts of the waterfront areas, and the resulting deformations caused minor damage to some engineering structures built on the reclaimed areas in the waterfront.

Two days after the earthquake, the University of Auckland team conducted reconnaissance inspection in the affected areas for three days (16-18 November), focusing on the performance of the ground and its impact to buildings and other civil engineering structures located in the waterfront. The affected areas were concentrated within the reclaimed areas adjacent to Lambton Harbour, with the degree of damage ranging from minor pavement cracks near Te Papa Museum in the southern side of the waterfront and becoming major towards north, i.e. at the location of CentrePort. Pavement cracks and ground subsidence were observed in varying degrees at various locations within the waterfront.

This paper summarises the major observations made by the team following the reconnaissance work. The region inspected covered a wide area, from the eastern side of the waterfront where Clyde Quay Wharf is located, to the northern side where Westpac stadium is sited. Further north, no damage was observed. An overview of the damage observed along the outskirts of Centreport are summarised, with more detailed discussions of the damage presented in Cubrinovski et al. [1]. It was noted that ground damage appeared to be concentrated in the areas reclaimed in the 1970s. The degree of damage was more or less comparable to the impact of the 2013 Cook Strait earthquake. Two areas where ground improvement works are known to have been implemented, the Te Papa Museum and Westpac stadium sites, were also inspected and they generally performed well.

HISTORY OF RECLAMATION

The Wellington waterfront is located on reclaimed lands on the shores of Lambton Harbour. The first large-scale reclamations took place in the 1850s, starting with land extension below Willis Street in 1852 (denoted by A in Figure 1). By the end of the 1870s, some 280,000 m^2 of land had been reclaimed by the Government, provincial and city councils by using spoil from the hills behind Lambton Quay and from Wadestown Hill [2]. The reclamation work was continued in several stages, with the boundaries of these stages depicted in Figure 1. The final phase of reclamation in the Harbour took place in the 1960s and 1970s where work was carried out on both side of Queens Wharf and, most significantly, the container terminal was created by a large reclamation at Thorndon [2]. Such work resulted in more space for the Wellington central business district and port facilities.

According to the report by Murashev and Palmer [3], most of the reclamations were constructed by end-tipping of gravel originating from roading and other excavation work being undertaken at the time, plus local quarries. They also reported that there is also an extensive area of hydraulic fill constructed by pumping dredged sandy harbour muds behind a mass concrete wall (reclamation Z on Figure 1). Some other limited areas of hydraulic fill are also reported to exist.

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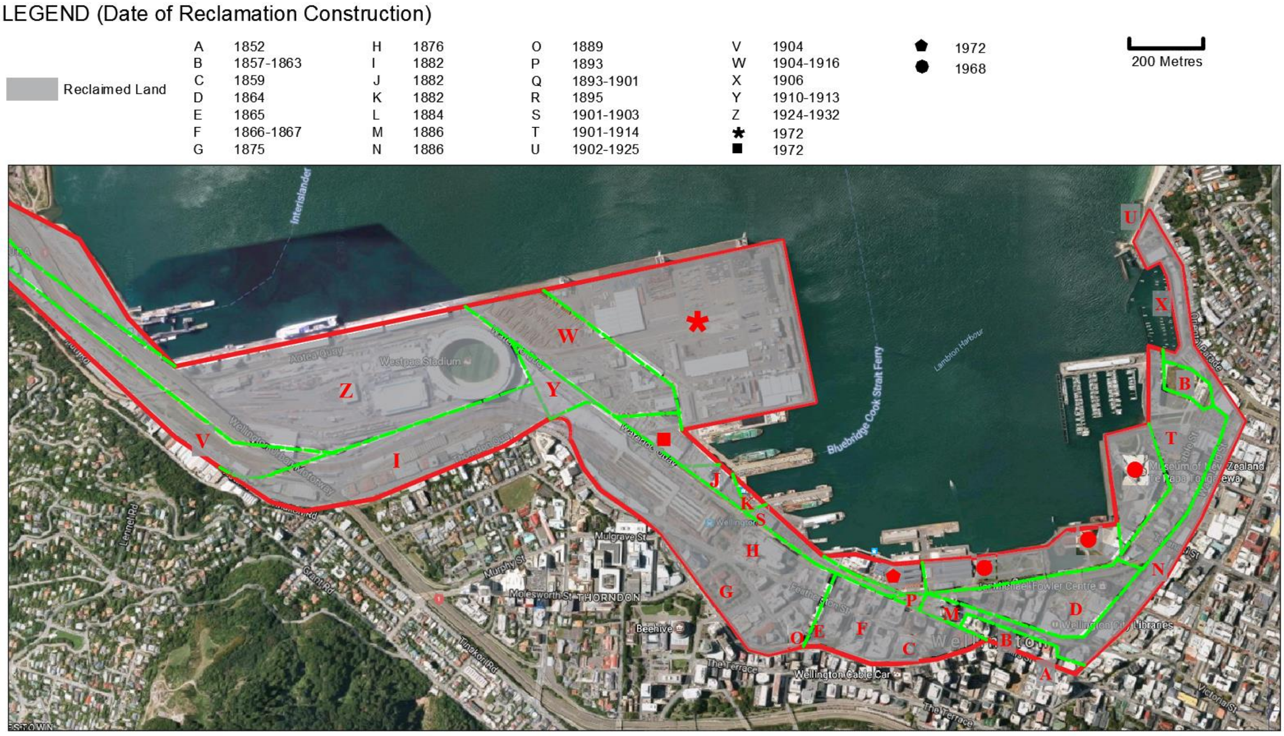

Figure 1: History of Wellington reclamations (from "Historical plan of reclamations in the port of Wellington (Port Nicholson)" by Wellington Harbour Board, as reported by Murashev and Palmer [3]).

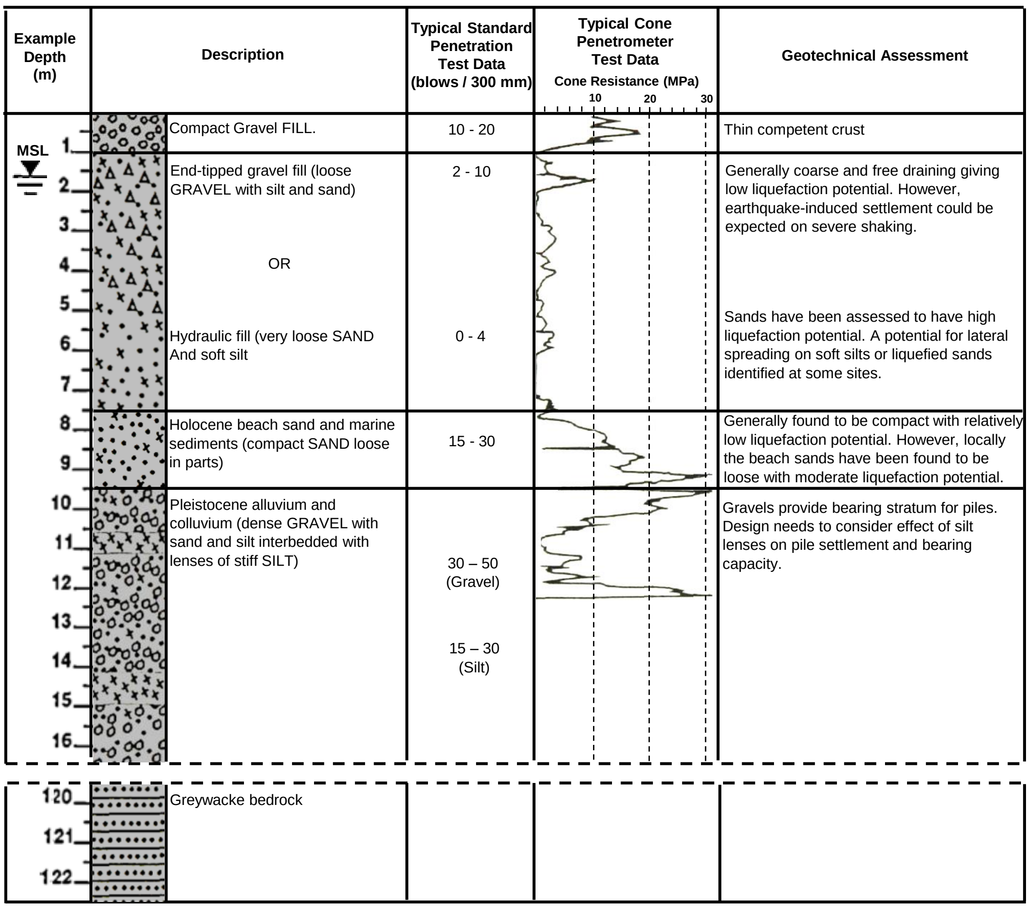

Figure 2: Typical soil profile at the Wellington waterfront area (adapted from Murashev and Palmer [3]).

Figure 3: An excavation site at the waterfront for a building, showing the exposed gravel fill.

As a result of the reclamation work, the ground in the reclaimed sites vary from soft silts and loose sands (dredged seabed material placed hydraulically) to loose silty gravel comprising weathered greywacke rock. The depth of reclamation varies up to 17 m. Typical soil profile is illustrated in Figure 2. The reclaimed land is approximately flat with ground surface levels varying between 1 – 3 m above the mean sea level [3]. During the reconnaissance work, there was an excavation for a building being constructed in the waterfront, where the gravel fill was exposed (see Figure 3).

STRONG MOTION RECORDS

In Wellington region, peak ground accelerations (PGAs) exceeding 0.2g were recorded in the CBD and Lower Hutt. Figure 4 shows the peak ground accelerations (PGA) recorded at GeoNet strong motion stations located at the waterfront; the horizontal PGAs indicated are the maximum of either NS or EW direction. At Victoria University Law School (VUWS) and Te Papa Museum (TEPS) stations, PGAs of 0.23g and 0.18g were recorded, respectively. At the CentrePort free-field site associated with the Frank Kitts Park (FKPS) and BNZ building (CPLB) stations, PGAs in the range of 0.16-0.24g were experienced, according to GeoNet records. More details of the strong ground motions in the area are reported by Bradley et al. [4]. Note that these strong motions are moderate compared to the level of ground shaking expected in the event of near field events, like the rupture of Wellington Fault (e.g. Stirling et al. [5]).

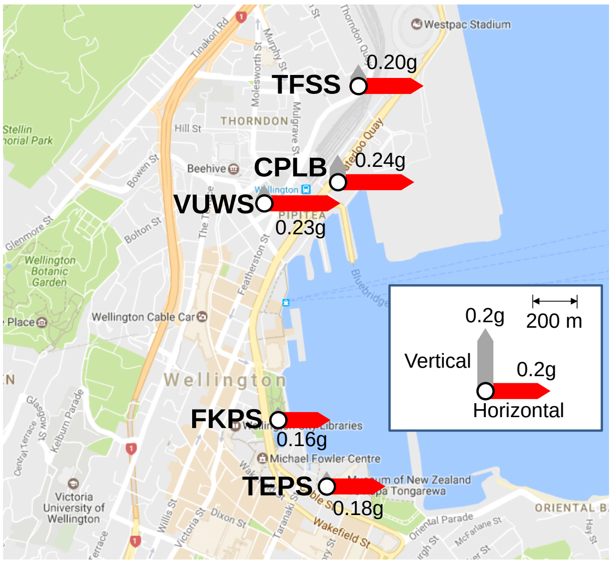

Figure 4: Wellington waterfront map of PGA measurements (data from GeoNet [6]).

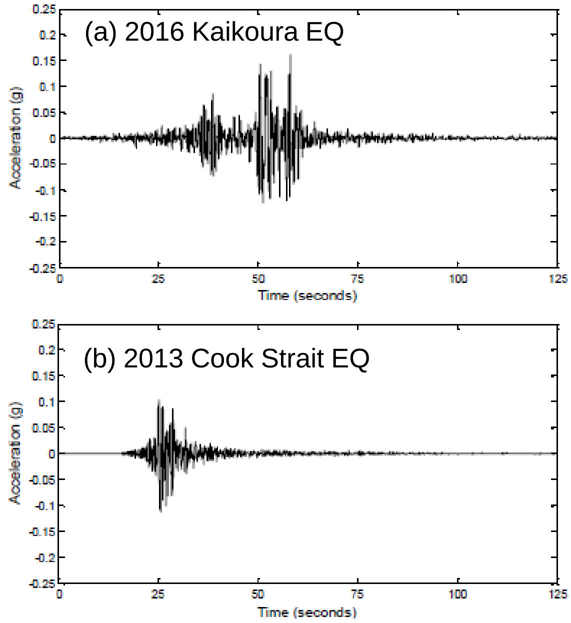

Figure 5: Comparison between the acceleration time histories recorded at FKPS station (N-S component) following the: (a) 2016 Kaikōura earthquake; and (b) 2013 Cook Strait earthquake (data from GeoNet [6]).

The recorded PGAs were more or less similar to those reported following the 2013 M6.6 Cook Strait earthquake sequence (e.g. Holden et al. [7]); however, the duration of significant shaking this time was longer (around 3-4 times), indicating that the grounds in the Wellington waterfront were subjected to more number of cyclic loading. Figure 5 is a comparison of typical earthquake records observed in the Wellington waterfront area following the two earthquake events.

DAMAGE TO WATERFRONT AREA

In examining the damage in the Wellington waterfront area, emphasis was made on the performance of the reclaimed lands adjacent to Lambton Harbour. The general route taken by the reconnaissance team is depicted in Figure 6, together with some of the landmarks used as reference in the discussion that follows.

Ground Damage

In the zone southeast of the TSB Bank Arena (designated as Zone A in Figure 6), the effect of earthquake shaking was minimal to non-existent. There was practically no damage observed in the paved areas adjacent to the sea wall, as depicted in Figure 7(a). Occasionally, minor cracks, about 2-5 mm wide and highlighted by spray paints, were observed in some sections, as portrayed in Figure 7(b). Unlike the occurrence of sand boils and ejected sandy/silty materials reported in Christchurch following the 2010-2011 Canterbury earthquake sequence (e.g. Orense et al. [8], Pender et al. [9]) and in Tokyo following the 2011 Great East Japan Earthquake (e.g. Orense et al. [10]), there was no manifestation of liquefaction adjacent to these cracks. Thus, it can be surmised that the damage was mainly the result of ground oscillation of the fill, although possible liquefaction-induced softening cannot be discounted. Referring to Figure 1, these zones were reclaimed in 1968; however, as discussed later, some parts of Zone A, such as the ground where the Te Papa Museum is located, have been improved to prevent liquefaction occurrence.

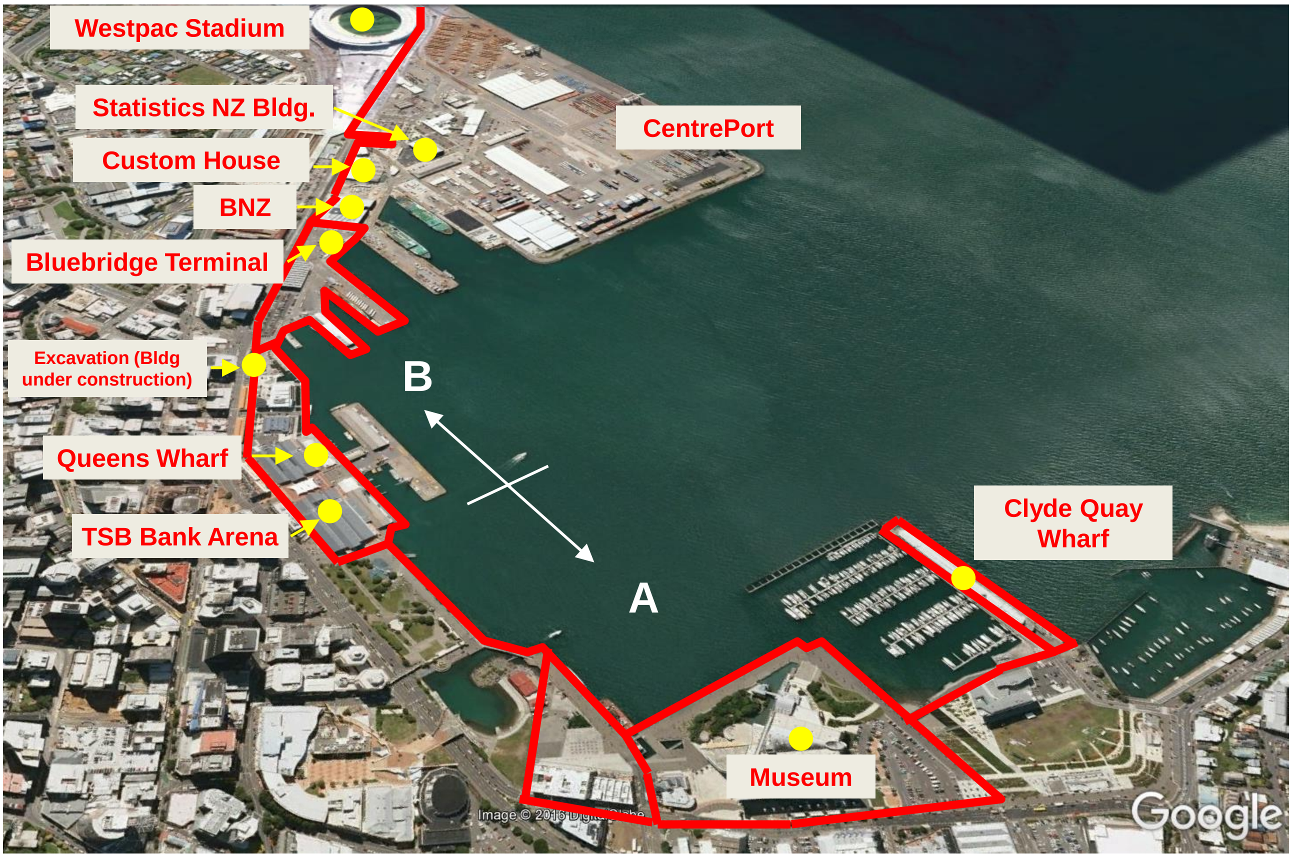

Figure 6. Location of sites and reconnaissance route.

Going north from the TSB Bank Arena Building/Queens Wharf area (referred to as Zone B in Figure 6), earthquake-induced ground damage became more noticeable. For example, Figure 7(c) shows a concrete barrier wall protruding from the retaining structure on the walkway which cracked as a result of the ground shaking. The crack exposed the steel reinforcement. Figure 7(d) illustrates a crack, 5-8 mm wide, running perpendicular to the walkway.

A significant number of moderate damages were observed in the parking area north of the Queens Wharf. In the area adjacent to a construction site (for location, see Figure 6), the ground subsided, resulting in 50-80 mm vertical gap between the walkway and the parking area, as shown in Figure 7(e). The subsidence is more noticeable in Figure 7(f), where the right section of the photo appears to be much lower (by about half a metre) compared to the left. Closer inspection revealed that a section of the wharf underwent significant settlement, as illustrated in Figure 7(g), and the backfill also subsided. Such subsidence may be attributed to the vertical compression of the weak embankment fill, although liquefaction may have also contributed (there are no reports that this section has been stabilised).

The pavement of the parking area north of the Queens Wharf was criss-crossed by many cracks. For example, Figure 7(h) shows a very long compressional crack, possibly induced by the shaking of the ground. In Figure 7(i), a section of a wharf was laterally displaced towards the sea, resulting in 60-80 mm crack opening and exposing a pipe underneath. Similar observation was noted in a section of another wharf, described in Figure 7(j). Note however that the location of the crack has asphalt sealant, indicating that this section may have cracked before (possibly after the 2013 Cook Strait Earthquake), and re-opened again following the ground shaking induced by the 2016 event. The intensity of ground shaking in this zone is described by the damaged foundation connection of a column supporting a fence, shown in Figure 7(k); the concrete base totally collapsed and the anchor bolts were exposed.

Proceeding north towards the Bluebridge Ferry Terminal building, which remained operational, cracks were observed on the sidewalk (Figure 7(l)); in addition, re-cracking of repaired pavement was evident, as shown in Figures 7(m) and 7(n). These cracks generally have no dominant orientation, although most of the cracks generally run parallel to the waterline.

Effect on Structures

Walking towards the north, 20-50 mm cracks on the ground, roads and pavements were still noticeable; however, since buildings are present in this area, the focus has shifted towards the performance of the structures in the reclaimed land.

Figure 8(a) shows the settlement of the ground adjacent to a shed building located in one of the wharves in the waterfront. The settlement induced a vertical gap of 30-60 mm near the shed opening. Although the ground settled, there appears to be no damage to the structure itself.

The ground adjacent to the southwest corner of the BNZ building settled by 50-80 mm, resulting in a noticeable gap between the building and the ground, as described in Figures 8(b) and 8(c). The building itself, which was evacuated after the quake, appeared to have no major structural damage but the interior showed damaged partition wall, ceiling, etc., mostly non-structural, as illustrated in Figure 8(d).

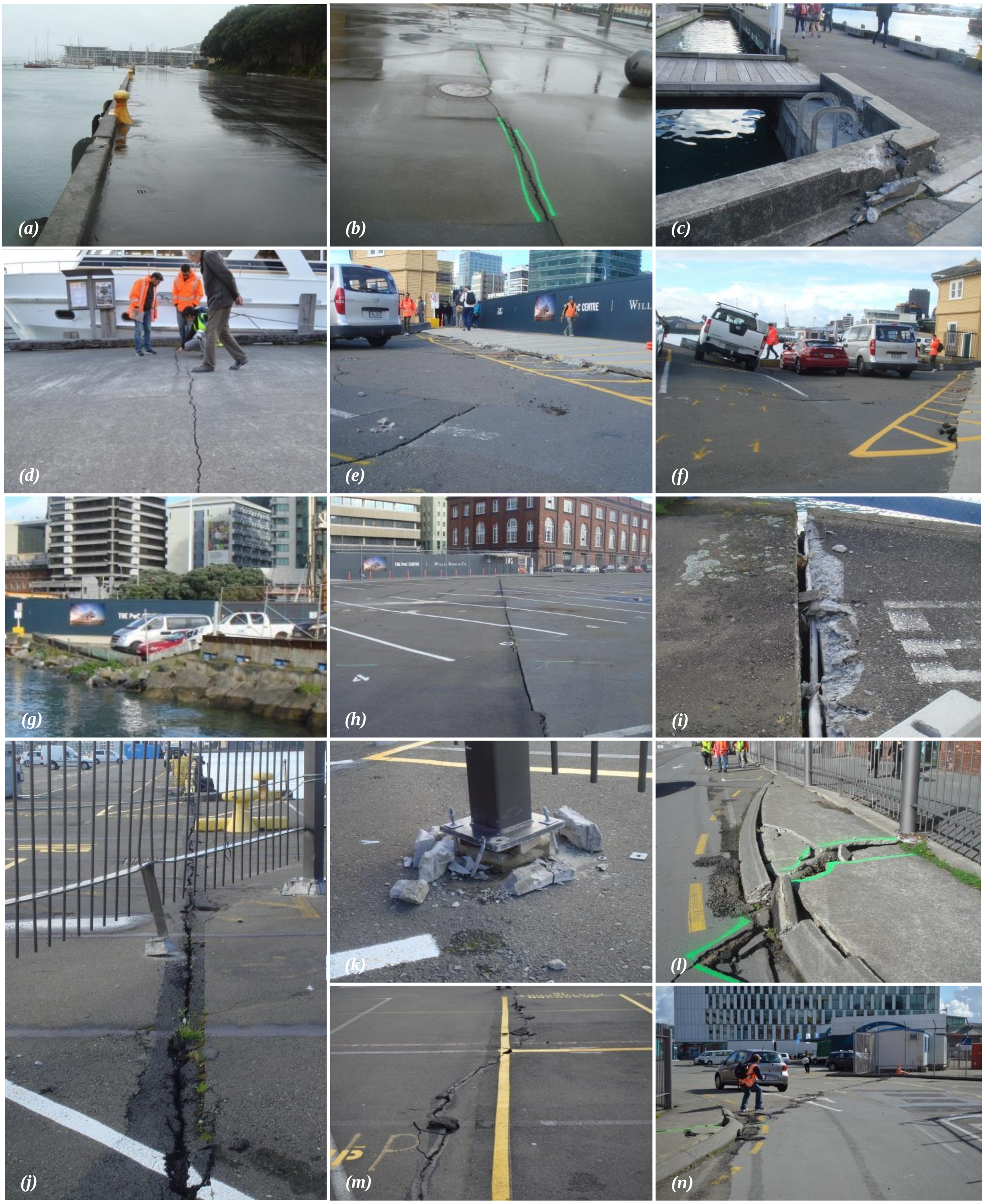

Figure 7: Various observations of ground condition in the waterfront area: (a) no visible damage at the back of Te Papa Museum; (b) minor crack on pavement, highlighted by spray paint; (c) broken concrete barrier on the waterfront walkway near Queens Wharf, with reinforcement exposed; (d) pavement crack perpendicular to the walkway; (e) ground settlement adjacent to construction site; (f) significant ground subsidence resulting in noticeable deformation; (g) another view of the ground subsidence in the parking area adjacent to the wharf; (h) long compressional crack on the parking area; (i) lateral movement of a section of a wharf, resulting in crack; (j) reoccurrence of crack on re-paved section of the wharf; (k) close-up view of the foundation connection failure of a fence column; (l) cracks on the sidewalk; (m) pavement crack on the parking area; and (n) crack on the parking area adjacent to the Bluebridge Ferry Terminal.

Figure 8: Various states of ground adjacent to structures: (a) ground settlement near a wharf shed; (b) settlement of the ground adjacent to BNZ building; (c) another section of BNZ building showing differential settlement between ground and structure; (d) non-structural damage to the interior of the BNZ building; (e) settlement of ground adjacent to the Customhouse building, resulting in vertical and horizontal offset; (f) cracked pavement and ground settlement near Customhouse building; (g) damaged brick pavement between Customhouse and Statistics NZ building; (h) destroyed pavement in front of Statistics NZ building.

Ground settlement, in the order of 20-60 mm, was continued to be observed in the area adjacent to the Customhouse building, located north of BNZ building. In the north section of the building, both vertical and horizontal offsets were observed (see Figure 8(e)); in addition, 10-20 mm cracks resulting from both horizontal and vertical ground movements re-appeared in sections which may have been repaired before, i.e. in areas filled with asphalt sealant, as illustrated in Figure 8(f).

East of Customhouse building, the Statistics NZ Wellington Office building was damaged by the earthquake; details of the structural damage are reported by Henry et al. [11]. Sand boils appeared intermittently in some locations adjacent to the building, while damaged brick pavements between the Customhouse building and the Statistics NZ building were observed (see Figures 8(g) and 8(h)), giving an indication of the possible strength of ground shaking in the area. Palmer [12] reported that the building is supported by piles; the foundation ground was described as consisting of gravel and sand as fill materials with SPT N-value between 10-20, which overlay a loose deposit of hydraulically filled sand and silt layer with SPT N value of 2-10. Based on this information and the indicated strength of ground shaking, soil liquefaction is the major cause of the ground settlement in the area. However, it is not clear how the softening of the ground induced by soil liquefaction affected the structural performance of the building.

Observed Damage from outside CentrePort

The Port of Wellington, officially referred to as CentrePort, is located in the northernmost reclaimed zone in Lambton Harbour. As indicated in Figure 1, the site of the port was reclaimed in 1972, making it one of the last reclamation projects in the harbour.

During the 2013 Cook Strait Earthquake (Mw 6.6; 21 July 2013) and the Lake Grassmere Earthquake (Mw 6.6; 16 August 2013), it was reported that extensive damage occurred in the container storage area located in the unrestrained southern end of the reclaimed land [13, 14]. Reports indicated a 250 m long section of western part of the southern end of the fill batter slumped, resulting in formation of lateral cracks 200-300 m long and 200 m wide. In addition, liquefaction-induced sand ejections were reported and many hairline cracks occurred much of the affected area, with subsidence occurring south of Shed 37.

Following the 2016 Kaikōura earthquake, significant damage again occurred at the port; details are discussed by Cubrinovski et al. [1]. It is apparent that the damage in this event was worse than during the 2013 earthquake. Some of the port's land subsided by more than half a metre, gantry cranes jumped off the rails and damage to wharves, seawalls,

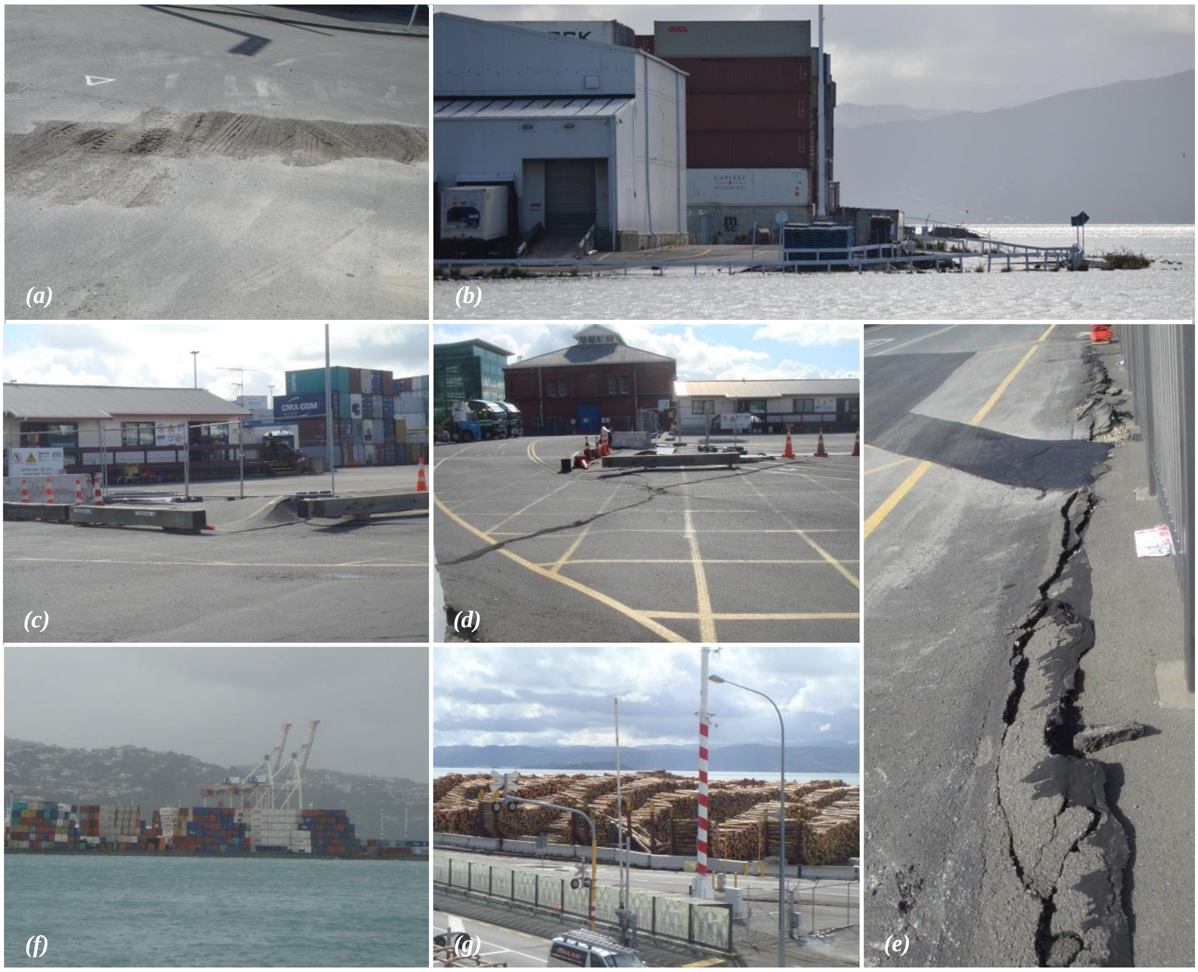

Figure 9: Damage observed from outside the CentrePort: (a) ejected sand and gravel near the entrance to the port; (b) south edge of Kings Wharf appeared to have settled and submerged under water; (c) subsidence within the port area; (d) longitudinal cracks on the pavement; (e) compressional ground cracks near the fence; (f) unstable stacking of containers in the yard; and (g) some logs falling off possibly due to shaking.

underground services and buildings were reported. Lateral spreading was also significant. One of the noticeable manifestations of liquefaction occurrence along the port boundaries was the sporadic presence of sand boils and cracks in the area. Figure 9(a) shows the ejected materials, consisting of coarse sand and gravelly material, at the port gate near the Customhouse building.

The south edge of the Kings Wharf settled and was under water, as illustrated in Figure 9(b). As mentioned earlier, the southern edge of the container yard underwent slumping following the 2013 earthquake; this time, the western end of the yard suffered the same fate. Other obvious damage was localised ground subsidence (Figure 9(c)), longitudinal cracks observed on the pavement (Figure 9(d)) and compressional cracks near the fence (Figure 9(e)).

Figure 9(f) shows the unstable stacking of the containers within the storage yard (as seen from Clyde Quay Wharf side), while Figure 9(g) illustrates some of the stacked timber logs falling off due to the ground shaking (as seen from Westpac Stadium).

PERFORMANCE OF IMPROVED GROUND SITES

Due to the nature of the ground in the Wellington's reclaimed waterfront and the number of development projects in the area, some sections necessitated the improvement/remediation of the ground to mitigate the potential for liquefaction and lateral spreading. Murashev and Palmer [3] reported extensive investigations, assessments and design work for some projects in the waterfront. Two improved sites are discussed here.

Te Papa Museum Site

The building housing the Te Papa Museum (officially called the Museum of New Zealand) is a base-isolated structure with concrete frames in one direction and concrete shear walls in the other direction to resist lateral loads. Wood and Martin [15] indicated the "the site has been reclaimed from the Wellington Harbour in two main stages. Prior to 1920, reclamation soil was deposited behind a concrete seawall to form Cable Street and some land beyond. In 1968, the main area of the site was created by end-dumping clean gravel and quarry material on the seaward side of the concrete seawall. A battered rock revetment beneath the present Taranaki Street Wharf retains the most recent reclamation and only 2 m was mechanically compacted". Murashev and Palmer [3] reported that site investigations identified the presence of loose reclamation fill with some potential for liquefaction over the depth range 8 to 13 m. The investigation work also identified the presence of a soft silt layer (often up to 1.4 m thick) entrapped between the reclamation fill (up to 13 m thick) and the underlying alluvial gravels and colluvium.

Based on these findings, it was resolved that ground improvement work be undertaken to mitigate liquefaction-induced damage, such as ground settlement and lateral spreading during strong earthquake shaking. For this purpose, remedial work was conducted using dynamic consolidation to

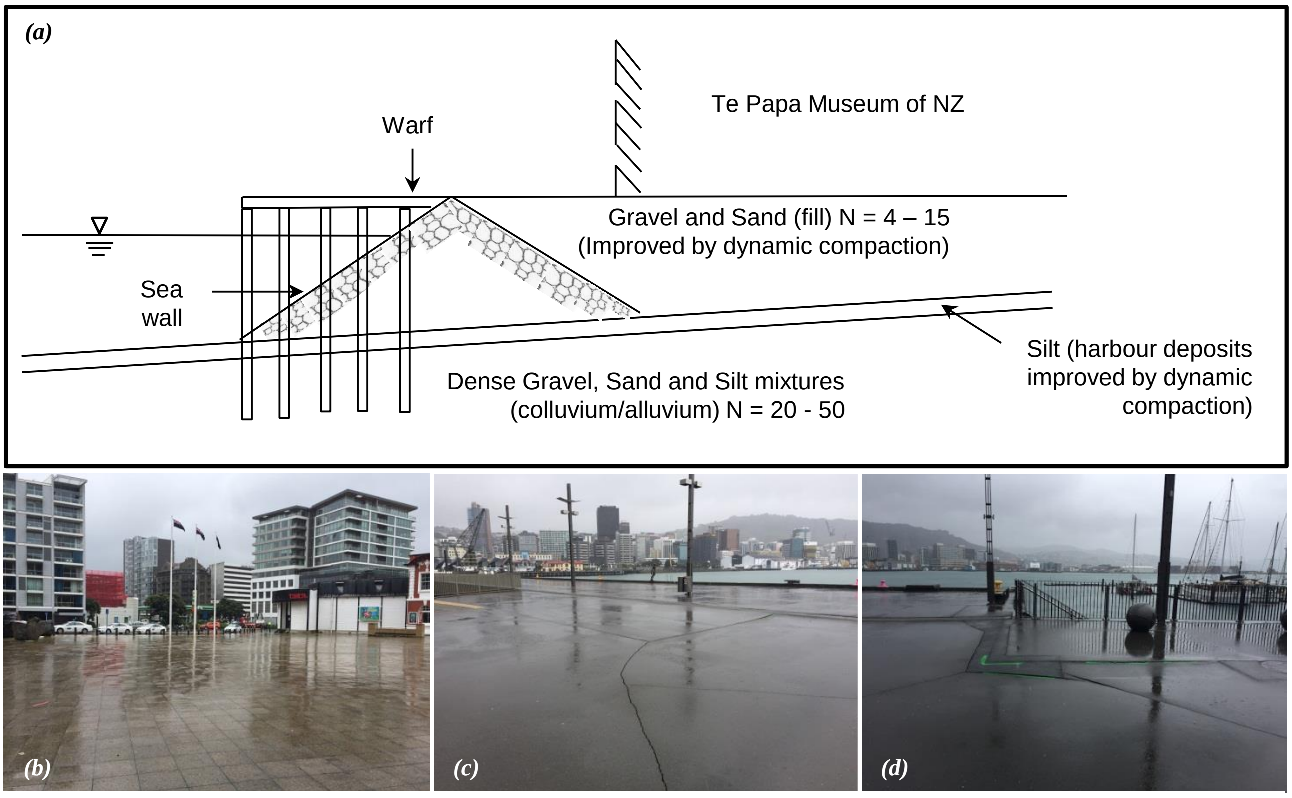

Figure 10: Condition near Te Papa Museum: (a) improvement of foundation ground by dynamic compaction (after Palmer 2006); (b) condition of pavement in front of the museum; (c) crack on the pavement at the back of the museum; and (d) minor slumping, resulting in vertical offset, near the seawall.

densify the reclamation fill and increase the strength of the underlying soft silt layer. The site profile as well as extent of improved ground is illustrated in Figure 10(a).

Following the 2016 earthquake, minor damage was observed on the pavement in front of the museum, which appeared to become wavy, which was confirmed by some inspectors interviewed by the team during the visit (see Figure 10(b)); at the back of the museum, minor cracks and slumping were noted at the wharf promenade, as illustrated in Figures 10(c) and 10(d).

Westpac Stadium Site

Murashev and Palmer [3] reported that the construction of the Westpac Stadium commenced in March 1998. They also reported that the site of the stadium “straddles two distinct areas of reclamation; one of hydraulic fill placed in the early 1930's and the other of end-tipped gravel fill placed in stages around the turn of the century.” To mitigate the potential impact of liquefaction in this high-capital value project, vibro-replacement method was adopted to produce gravel columns of 0.8 m to 1.2 m in diameter on a grid at spacing of 2 – 3 m. The stadium itself was supported by driven pile foundations. Figure 11(a) illustrates the extent of improvement and typical cross-sectional profile underneath the stadium.

Following the 2016 earthquake, the stadium escaped unscathed and no ground damage was observed in the foundation ground, as seen in Figure 11(b). However, a portion of the sidewalk on the eastern side of the stadium (along Waterloo Quay Street) buckled (see Figures 11(c) and 11(d)) and underground utilities may have been compromised (Figure 11(e)). In addition, a 60 mm gap between the sidewalk and the roadway can be seen, as described in Figure 11(f). This isolated damage occurred at a section opposite the CentrePort, possibly at the boundary between the improved and the unimproved ground; the inferred location is indicated in Figure 11(a).

Overall, the foundation grounds improved by liquefaction countermeasure techniques discussed above performed very well. Such excellent performance may be attributed to the good design of the improvement scheme adopted; however, it should be mentioned that the level of shaking experienced by these improved sites during the 2016 event may be moderate. Similar to the observations made by Wotherspoon et al. [16] following the Canterbury earthquake sequence, the improved ground sites may not have been actually tested because of the moderate PGAs the sites have experienced. Re-assessment of their performance considering say a Wellington Fault rupture scenario may be necessary.

SUMMARY

Following the inspection of Wellington waterfront after the earthquake, the main observations are summarised as follows:

- Based on the history of Wellington reclamation, ground damage in the form of cracks, ground settlement and fissures, appeared to be concentrated in recently reclaimed areas, as late as in the 1970s. Liquefaction-induced ground damage in Wellington was concentrated in the waterfront area north of the Queens Wharf.

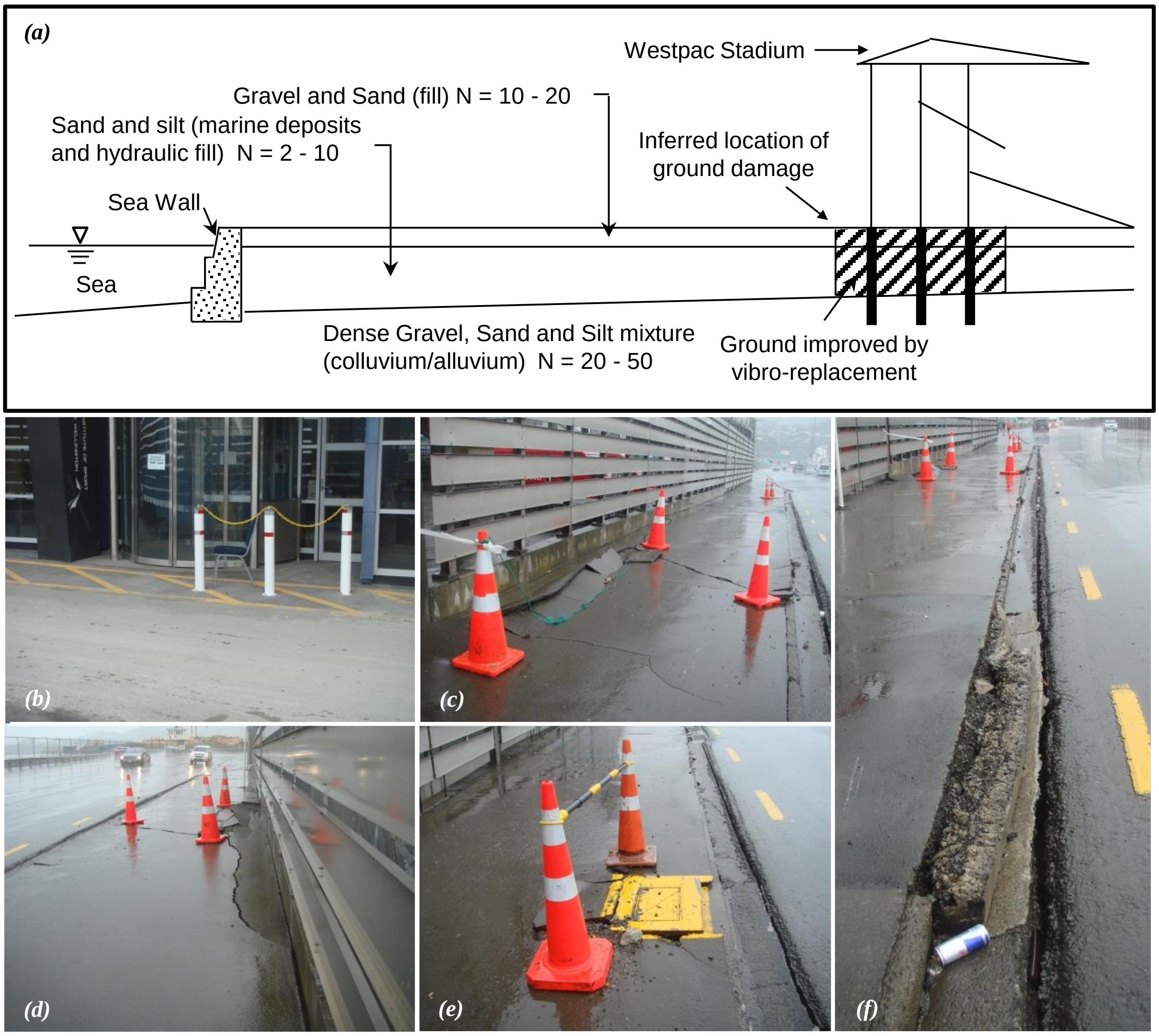

Figure 11: Condition near Westpac Stadium: (a) improvement of foundation ground by vibro-replacement method (after Palmer 2006); (b) no visible foundation ground damage at the stadium; (c) buckling of the sidewalk adjacent to the stadium; (d) another view of the deformed sidewalk; (e) ground damage adjacent to utility cover; and (f) wide crack between sidewalk and road.

- Significant damage was evident across Centreport, induced by the liquefaction of the reclaimed ground. Ground subsidence, cracks, differential settlements and other forms of ground movements have been observed.
- Ground adjacent to buildings along the waterfront, such as near the BNZ building, Customhouse building, and Statistics NZ building, showed evidence of moderate settlement. Pavement buckling and cracking were also observed. These were mainly the result of ground oscillation and possible densification of the weak embankment fill, but liquefaction may have contributed in some instances.
- The improved ground sites at the location of Te Papa Museum and Westpac Stadium performed well, with no significant damage observed; minor ground failure was noted at the boundary between the improved and non-improved grounds of Westpac stadium. It is possible that these sites were not really tested, because of the smaller-than-expected PGAs experienced by the area.
- The PGAs recorded in this event were more or less similar to those observed following the 2013 earthquake sequence; however, the longer duration of shaking and, consequently, the larger number of significant cycles may have contributed to greater liquefaction-induced ground damage observed in this event, especially in the unimproved ground at the CentrePort.

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