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Liquefaction Induced Flooding in Christchurch, New Zealand

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ABSTRACT

Large, low-lying tracts of eastern Christchurch, New Zealand, were inundated multiple times with water several centimeters deep as a result of earthquake-induced liquefaction processes initiated by the main events in the 2010-2011 Canterbury earthquake sequence. The water and soil ejection process from liquefaction is well understood. However, the extent of possible ejecta and the resulting impacts on communities are neither understood nor documented. This paper presents observations and some lessons learned from the liquefaction-induced flooding and sedimentation experienced in Christchurch. These processes resulted in costly damages to private properties and to the water, sewer, storm water, and transportation lifelines systems as well as hindering people's mobility and access to emergency services in the earthquake aftermath. Additionally, emergency response and recovery activities were delayed or hindered. Results of this initial investigation identify the need for better understanding of the conditions leading to severe liquefaction-induced flooding and sedimentation to allow for improved public policy and engineering mitigations.

Introduction

Between Sept. 4, 2010 and Dec. 23, 2011, the Canterbury, NZ region was shaken by a historically unprecedented earthquake sequence which caused extensive liquefaction in and around Christchurch. In many areas the liquefaction was so severe it resulted in flooding across large areas for many hours to days following the earthquake. This water and soil ejection process from liquefaction is well understood. However, the extent of possible ejecta and resulting community impacts is not well understood or well documented. The 2010-11 earthquake sequence provides unique examples of extensive liquefaction in numerous communities who suffered flooding primarily from water and soil being ejected from the ground as a direct result of the liquefaction process. The purpose of this paper is to provide initial documentation of these examples and the resulting impacts to infrastructure. The study summarized herein is part of a much broader on-going international project investigating earthquake-flood multihazard impacts to lifeline systems.

Canterbury, New Zealand, Earthquake Sequence of 2010-2011

The Canterbury, New Zealand region was struck by a sequence of earthquakes in 2010 and 2011; the most significant being: M_w 7.1 on Sept. 4, 2010; M_w 6.2 on Feb. 22, 2011; M_w 5.8 and M_w 6.0 on June 13, 2011; and M_w 5.8 and M_w 5.9 on Dec. 23, 2011. The 2010 earthquake epicenter

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was located 45 km west of Christchurch while the 2011 earthquakes were about 6 to 10 km from the Christchurch city center. This earthquake sequence resulted in significant seismic-induced geotechnical mechanisms increasing flood susceptibility in the Christchurch area, including vertical tectonic movements, liquefaction induced settlement, and lateral spreading. This paper focuses on liquefaction-induced flooding and sedimentation. Other geotechnical aspects are part of on-going earthquake-flood multihazard studies (e.g., GEER, 2014).

Earthquake-Induced Liquefaction Process Leading to Flooding

Figure 1 shows flooding after the February 22, 2011 Christchurch earthquake resulting from large volumes of liquefaction-induced water bubbling out from the ground in portions of the city, which was compounded by water flowing from broken pipes and groundwater wells. The liquefaction process is well understood and can be found in numerous references (e.g., Idriss and Boulanger, 2008). This section does not provide new information on the liquefaction process, but instead summarizes the process as it relates to the flooding observed in the Canterbury region, using surficial flooding and erosion as an analogy, and provides a technical context for the impacts on community and lifeline systems.

Figure 1. Typical liquefaction induced flooding of Christchurch suburbia from Feb. 22, 2011. (a) Aerial view of estuary-proximal suburb of Bexley (Crown Copyright 2011, NZ Defence Force – Some Rights Reserved). (b) Flooding of Anzac Dr. (courtesy T. O'Rourke).

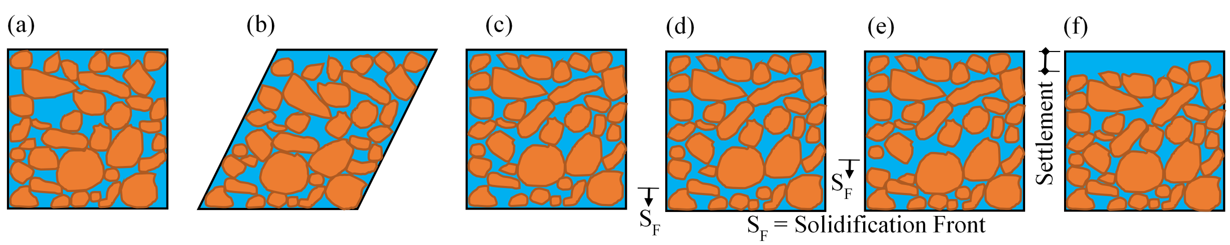

Figure 2. Saturated soil element experiencing undrained shear strain from earthquake shaking, liquefaction, and solidification. (a) Initial un-sheared state with particles supported by grain-to-grain contact. (b) Element experiencing shear deformation rearranging the soil particles. (c) Element returned to un-sheared condition after developing maximum pore pressure (liquefaction) with particles in a suspended condition. (d) Particles in liquefied element begin to fall out of suspension showing initiation of solidification front S_F. (e) Solidification front propagating upward. (e) Element with particle arrangement in final solidified state showing final settlement.

Figure 2 diagrams the liquefaction process. Liquefaction generally occurs in loose, saturated or partially-saturated non-cohesive soils. During earthquake shaking, the granular soil contracts decreasing in volume. The volume decrease occurs as the soil particles move and attempt to fill the void spaces within the loose soil mass. In saturated soils, the void space is filled with water. If drainage is unable to occur during the shearing and contraction process (Fig. 2b) the incompressible water temporarily prevents the soil grains from contracting (Fig. 2c). As the soil void space attempts to decrease, the load is transferred from the soil structure to the water mass, resulting in an increase in pore water pressure and stress reduction on the soil grains. Water pressure can build up to a value equal to the overburden pressure, at which point the effective stress drops to zero, creating a liquefied condition, and the soil grains are put in a state of suspension (Scott, 1986) as shown in Figure 2c.

The excess water pressures generated in the soil mass are dissipated by solidification and water flow. The water flow tends to move upward due to an upward hydraulic gradient (Idriss and Boulanger, 2008). The water flow initiates from the bottom of liquefied soil layers as the particles settle by falling out of suspension (Scott, 1986) as shown in Figure 2d, and creates an intra-layer water gap or loose soil zone as shown in Figures 2d and 2e. Figure 2e shows the upward propagation of a particle solidification front through a soil element, which eventually results in total settlement within the element as shown in Figure 2f. This is a constant volume process which is understood by comparing Figures 2a and 2f. These figures show how the soil particles are rearranged within the same unit volume and during settlement the water moves upward relative to soil particles, but the top of water gap or water film shown in Figure 2f is the same elevation as the original top of the soil grains shown in Figure 2a.

As shown in Figure 3, in large soil deposits intermediate soil layers having lower permeability (e.g., a very thin silty layer above a massive sand layer) may reduce the rate of flow causing build-up of a water film and lateral water flow. The generation of water films add to the potential ground instability which may already exist due to reduced soil strength. The unstable condition results in ground deformations and cracking. Tension cracks provide a low resistance path for water to escape during the pore water pressure dissipation process. As the pressures dissipate, the natural subsurface variability results in changes to the hydraulic gradient.

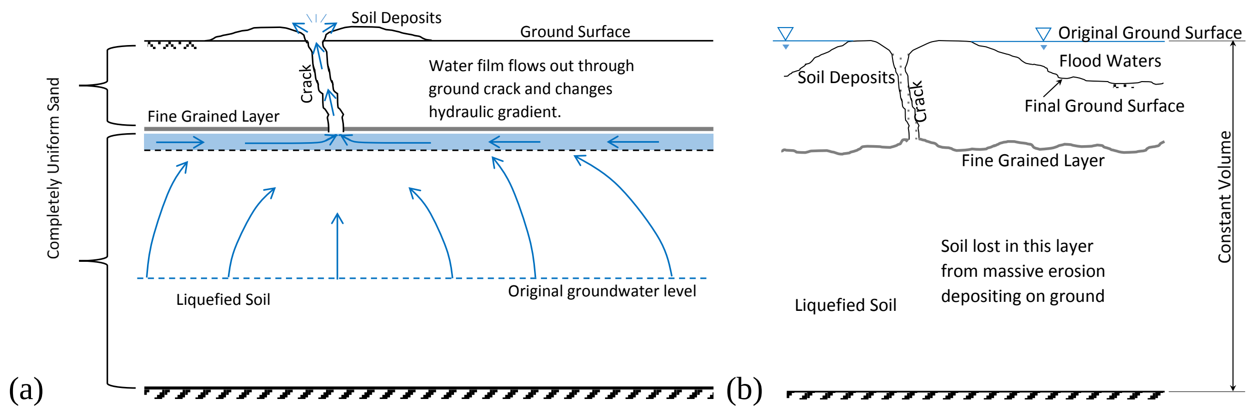

Figure 3. Continuous fine grained layer within otherwise uniform sand. (a) Upward water flow slowed at fine grained layer forming a water film; crack focuses soil-water slurry ejection on ground surface and changes hydraulic gradient. (b) Final state of uneven ground conditions.

The formation of cracks and water films in the subsurface tend to focus the flow paths and create complicated flow conditions and hydraulic gradients. The hydraulic gradients commonly have sufficient velocity and force to erode subsurface soils. The soil particles in a liquefied state are in a buoyant condition and highly susceptible to erosion. In fact, the initial hydraulic gradient set up in a liquefied soil mass is analogous to initiating piping erosion or quick conditions (Idriss & Boulanger, 2008). Soil erosion takes place along the subsurface water flow paths. Rapid flowing water picks up soil particles along its course. In some cases the soil being eroded may not have been liquefied, but simply located on the path of least resistance for pore water pressure dissipation. This erosion process creates a soil-water slurry, which flows as described above for subsurface water paths.

The water or a soil-water slurry flow is ejected from the earth, either onto the ground surface, or into some subsurface cavity such as an underground vault, cracked or open pipe or other space. The observable ejecta are shown in Figure 3 as a water flow, often accompanied with soil when erosion takes place. Soil ejected onto the ground is commonly referred to as “sand boils”, “mud spouts”, or “sand volcanos” as a result of the ejection process looking like material boiling up or spouting from the ground, with resulting deposits forming cone-shaped mounds with central craters akin to mini-volcanos as shown in Figure 3 and Figure 5a presented in a later section.

Because liquefaction is a constant volume process, as the ground settles the water and soil sedimentation deposition depth above the ground increases and inundates the surface as shown in Figure 3b. In the absence of surface drainage, the water surface elevation after the liquefaction process is completed remains approximately the same as the original pre-earthquake ground surface elevation. The variation in subsurface conditions and erosion process results in differential settlement across the ground surface. The inundation depth of flooding is approximately equal to the settlement when original groundwater is near the surface.

Analog with Surface Water Flooding

The liquefaction-induced flooding from the groundwater has an analogy with surface water flooding. Flooding occurs from the accumulation of source water of sufficient volume to inundate areas of land. Normally this occurs from water above ground such as rain, snow melt, dam/levee failure, etc. The hydraulic gradient created from water flow may be sufficient to erode soil and move other materials, which can then be transported and deposited downstream as debris. During the liquefaction process the groundwater serves as the source water, which can erode the subsurface soils and deposit them where the water is ejected from the ground. This analog is useful for relating the liquefaction-induced flooding and sedimentation to other more common flood events created from surface waters and associated sediment and debris deposition.

Liquefaction-Induced Settlement and Flooding in Christchurch, NZ

Ground settlements resulted from multiple geotechnical mechanisms including: (1) head ward vertical slumping from lateral spread movements, (2) solidification of liquefied soils, and (3) loss of ground from the subsurface soil erosion and ejection process. Approximately 87% of the settlement is estimated to be associated with the ejecta (Van Ballegooy et al., 2014). These settlements increased the flooding opportunity by providing lower laying areas for water to pond as shown in Figure 1b. Settlements from solidification and soil ejection occurred as the liquefaction-induced floodwaters were ejected to the ground surface; that is, the ground was settling as water was ponding on the lowered ground surface. In a sense, a bowl shape was formed giving an area to hold the ejected water. As shown in Figure 1, many streets were inundated with water several tens of centimeters deep. Vast volumes of surface deposits were removed after each event, combining with the accumulation of the three primary settlement mechanisms to enhance the liquefaction-induced flooding potential for each subsequent earthquake event. Cumulative settlement reached 0.3 to 1 m in different areas (GEER, 2014).

Liquefaction-induced flooding occurred in Christchurch city and nearby towns in all the previously identified significant earthquake events within the sequence. Figure 4 presents some examples of liquefaction-induced flooding in different locations and earthquakes. Not all liquefied areas sustained flooding following the earthquakes. Many areas experienced liquefaction-induced water and soil ejecta at the ground surface, without experiencing flooding, due to insufficient water spouting from the ground, little or no damage to pipelines, and/or sloped ground allowing ejected water to drain rapidly. Some areas experienced liquefaction induced flooding from several of the earthquakes, while other areas only experienced flooding from a single event. Those areas which experienced liquefaction-induced flooding were generally low-lying and relatively flat, underlain by thick soil deposits having a relatively high liquefaction potential and, crucially, featured shallow groundwater. Communities suffering significant liquefaction-induced flooding in at least one earthquake include: Aranui, Avondale, Avonside, Bexley, Bromley, Burwood, Central City, Ferrymead, Halswell, New Brighton, Parklands/Queenspark, Richmond, Shirley, Wianoni, and Woolston/Brookhaven. Large inhabited areas were inundated, as seen in Figure 1, in all events resulting in liquefaction-induced flooding of streets and properties, including homes and businesses. In total these areas directly impacted at least tens of thousands of people multiple times resulting in extensive infrastructure and property damages and associated economic impacts. Observations were also made in large open park spaces and rural fields, where no developments or underground piping exist. While these rural areas may have suffered little-to-no economic impact, they do provide evidence for the source of flooding coming from the liquefaction process. Further evidence comes from flooding in urban areas at elevations above river level, and in backyards contained by walls and fencing (e.g., Figure 4b; https://www.youtube.com/watch?v=gDkLPLCC_Ok).

(a) (b) (c)

Figure 4. Liquefaction-induced flooding impacts. (a) Feb 22, 2011 flooded street in Aranui suburb. (b) June 13, 2011 flooded property in Aranui suburb. (c) June 13, 2011 flooding streets and property in Bromley. (Photos courtesy M. Lincoln, nzraw.co.nz)

Figure 1b shows a photograph of flooding on Anzac Dr. following the Feb. 22, 2011 earthquake in the Bexley suburb. The water depth at time the photograph was taken is estimated as 200 to 300 mm based on curbs completely covered with water and the car bumper in the background above water. Settlement in Bexley was about 300 mm for this earthquake. The reported settlement and observed flood depths are consistent with liquefaction ejecta causing flooding, as seen in Figs. 2 and 3. Further investigations are warranted to confirm these initial observations.

Damaged infrastructure contributed to the liquefaction-induced flooding in several ways. Damaged pressurized water pipes and wells added to the volumes of flood water, and in some cases created localized flooding. The damaged sewer and storm water drainage pipes were filled with sands, reducing or completely eliminating their ability to drain water. Upstream wastewater flows were either: (1) backed-up and flooded upstream at points where the hydraulic head reached the ground surface elevation, or (2) discharged at the point of damage adding to local flood conditions.

Impacts From Liquefaction-Induced Flooding and Sedimentation in Christchurch

Damaged non-pressurized pipes from sanitary sewer and storm water drainage networks created open void spaces into which the subsurface liquefied soils flowed. Additionally, the increased hydrostatic pressures placed buoyant forces on buried pipes, potentially displacing and opening the pipe joints and/or causing the pipes and appurtenant structures to float. Sewage water discharge contaminated some flooded areas causing health concerns. The flood water eventually drained to rivers, estuaries and the ocean, thereby spreading the contamination. Also, as part of the immediate response, raw sewage was pumped into local rivers within the city.

Figure 5 presents example impacts from liquefaction-induced sedimentation. Large volumes of soil were ejected onto the ground surface and flowed considerable distances which: (i) blocked drainage paths, (ii) filled catch basins, (iii) blocked streets, and (iv) trapped vehicles. Items (i) and (ii) prevented drainage of liquefaction-induced inundation while items (iii) and (iv) reduced or eliminated street functionality. The damaged pipes eroded large holes in the streets and further impacted transport capabilities through (1) soil flowing into non-pressurized sanitary sewer and storm water drainage pipes and (2) pressurized water pipes jetting and eroding holes.

(a) 
(b) 
(c) 

Figure 5. Liquefaction-induced sedimentation impacts. (a) Feb. 22, 2011 liquefaction sediments forming cones (Curtesy T. Musson, commons.wikimedia.org). (b) Feb. 22, 2011 car partially buried in sediments (Courtesy G. Gho, commons.wikimedia.org). (c) June 13, 2011 street blocked by liquefaction sediments and trapping vehicle (Courtesy M. Lincoln, nzraw.co.nz).

In addition to the drainage problems, the sediments ejected onto the ground surface built up very large sand volcanos with high, steep cones and wide, deep craters capable of bottoming out vehicles attempting to cross over them (e.g., see http://izismile.com/2012/08/31/ christchurch_liquefaction_26_pics-11.htm and http://mauriroawaitaha.wordpress.com/). As seen in Figures 4b and 4c, sediment build-up was sufficient to partially bury automobiles and block streets (see also for example, http://keithwoodford.wordpress.com/2011/02/27/understanding-the-christchurch-earthquake-building-damage). Some people became temporarily trapped in their cars as a result of sediment blocking their doors (http://news.wikinut.com/Earthquake-strike-s.-February-the-22nd-2011/19occxnq/). Roadways were choked with vehicles stuck in the loose saturated sediment (http://www.stuff.co.nz/national/photos/4688271/Christchurch-aftershock-Feb-22; https://quakestudies.canterbury.ac.nz/store/part/88391).

Sediment also flowed into subsurface sewer and storm water drainage pipes as depicted in Figure 6a. This flow into pipes caused several problems, including: (1) blocking sewage flow leading to sewage flooding into streets, rivers, and estuaries causing widespread contamination, (2) blocking drainpipe flow preventing drainage of liquefaction-induced flooding and enhancing the post-earthquake flood problems, and (3) sinkholes in the streets impacting transportation, mobility, safety, other nearby utilities, private property, and emergency response. Additionally, some holes were eroded from damaged pressurized water pipes.

(a) (b) (c)

(d) (e) (f)

Figure 6. Sinkholes. (a) Car being pulled into sinkhole along with liquefaction sediment flow. (b) Dump truck stuck in sinkhole obscured by water. (c) Fire engine stuck in hole Sept. 4, 2010 (Courtesy B. Richardson, nzraw.co.nz). (d) Car drove into sinkhole previously obscured by water. (e) Large sinkhole swallowing street, vehicles, and power pole (Courtesy Perduta commons.wikimedia.org). (f) Car completely engulfed within sinkhole. All photographs except (c) are from Feb. 22, 2011. All photographs except (c) and (e) courtesy M. Lincoln, nzraw.co.nz.

The subsurface erosional flow of sediments into a pipe or other subsurface void space creates different types of impacts, as shown in 6, than when the eroded sediments are ejected onto the ground surface. The sinkholes and sediment in the streets inhibited emergency response and recovery activities ranging from emergency response vehicles shown in Figure 6c to construction equipment shown in Figure 6b to emergency water tanker trucks (e.g., http://izismile.com/2012/08/31/christchurch_liquefaction_26_pics-11.html). In many cases these sinkholes were obscured by flood waters as indicated in Figures 6b and 6d and vehicles unknowingly drove into these holes as circled in Figure 4a. As water subsided the holes retained water, and people drove into them believing they were passing over a puddle not knowing the ponding represented a deep hole (http://news.wikinut.com/Earthquake-strike-s.-February-the-22nd-2011/19occxnq/). In other cases the sinkholes developed directly below vehicles and sucked them into the formation. Figure 6e exemplifies how some sinkholes were very large and dangerous, opening entire streets, affecting not only transportation corridors and vehicle safety, but also other lifelines in the street and private properties.

In a few cases the sinkholes posed threats to lives, where vehicles either sank or drove into sinkholes, or sank into surficial liquefied soils having no bearing strength (e.g. see in Figure 6f the same car as circled in Fig. 4a). A few vehicles became engulfed to the extent drivers and passengers could have drown. Additionally, there is documentation of people being trapped in holes from the September 4, 2010 and June 13, 2011 earthquakes, and at least in one case a lady was noted to have to claw her way out of the liquefaction (see for example http://www.abc.net.au/news/2011-06-15/liquefaction-traps-christchurch-resident/2759046 and http://www.nzraw.co.nz/news/fire-engine-stuck-following-christchurch-earthquake/). There are no documented cases of severe injuries or fatalities in Christchurch resulting from this hazard.

Conclusions

Few, if any, studies have investigated liquefaction-induced flooding and sedimentation impacts on lifeline systems. The liquefaction ejecta process was well documented and observable in social media posts (e.g., youtube.com and flickr.com), providing strong evidence of liquefaction-induced flooding. The Canterbury earthquake sequence highlights the rare but extreme inundation problems that can arise from liquefaction processes. Christchurch also provides a unique opportunity to investigate and document numerous liquefaction inundation impacts on communities. Such documentation is helpful to prepare for similar potential problems in other areas. The geotechnical and urbanized development conditions leading to such extenuating situations needs further investigation so guidelines for public policy and engineering mitigations can be developed and used worldwide.

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