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PERFORMANCE OF LIGHTWEIGHT STRUCTURES DURING LIQUEFACTION FROM RECENT EARTHQUAKES

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ABSTRACT

Several case histories of lightweight structures performance during liquefaction from recent earthquake are reviewed. The review is focused on performance of lightweight structures in terms of liquefaction-induced vertical settlement, tilting, lateral displacement and their effects on occupancy and functionality of the structures. These case histories were reported during the 1997 M_w 7.4 Caucete-Argentina, 2007 M_w 8.0 Pisco-Peru, 2010 M_w 8.8 Chile, 2010 M_w 7.2 El Mayor-Cucapah, 2010-2011 New Zealand, and 2011 M_w 9.0 Great East Japan earthquakes. The review is performed to identify similarities, discuss conditions, and their effects on foundation and structures. Financial and economic considerations are discussed and compared for housing, i.e., cost of housing versus cost of strengthened foundation and/or improved ground. Some recommendations for residential areas are proposed.

INTRODUCTION

During the 1997 Caucete-Argentina earthquake, possibly thousands of square kilometers liquefied affecting hundreds of one-story houses and inducing settlements as great as one meter. The 2007 Pisco-Peru earthquake caused liquefaction along coastline areas for approximately 300 km long damaging hundreds of lightweight structures. A town of fishermen with more than 100 one-story and two-story houses in a port located in front of the epicenter was completely liquefied and settlements were as much as approximately one meter. The town was partially relocated. The 2010 El Mayor-Cucapah earthquake liquefied an entire valley south of Mexicali city, Mexico, and hundreds of farmers' houses were seriously damaged and subject to partial collapse and several to the verge of total collapse. The 2010-2011 New Zealand Canterbury earthquakes liquefied large areas with residential developments and entire neighborhoods were relocated after the earthquakes because of the severe disruption caused by liquefaction. The 2011 Great East Japan earthquake damaged hundreds of lightweight modern one-story and two-story structures reporting significant settlements, disrupting lifelines (water, sewage, power, communication) and affecting the real estate market especially in fancy residential areas in Tokyo such as Urayasu. The Japanese government is providing tax incentives and subsidies for people whose houses are located in areas susceptible to liquefaction.

This paper presents the results of review of case histories and pertinent literature review of liquefaction-induced lightweight building settlements and proposes specific recommendations for residential areas.

1997 M_w 7.4 CAUCETE, ARGENTINA EARTHQUAKE

Caucete is a city in the province of San Juan, Argentina. The epicenter of this destructive earthquake was located approximately 80 km northeast of the city of San Juan. The shallow main shock triggered landslides and liquefaction in the epicentral area. Several hundred square kilometers, and possibly thousands of square kilometers, were affected by liquefaction in low areas north and northwest of the epicenter. Hundreds of adobe and brick masonry housing partially or completely collapsed as a result of induced soil movements due to liquefaction. Surface manifestation of liquefaction included not only sand boils but large linear and arcuate fissures. Reports indicate that this feature was one meter wide and more than two meters deep. Also it was reported vertical movements up to approximately one meter (NISEE 1997; EERI 1997). Figures 1a and 1b present some representative liquefaction-induced damage to one-story houses.

Figure 1a. Liquefaction-induced differential settlement of a one-story masonry house (NISEE 1997)

Figure 1b. Damaged reinforced concrete slab of same one-story masonry house (NISEE 1997)

2007 M_w 8.0 PISCO, PERU EARTHQUAKE

This earthquake caused severe ground-failure induced damage to urban and transportation infrastructure over a wide region south of Lima, the capital of Peru. Widespread foundation bearing capacity failures induced by liquefaction of about one hundred relatively light weight one- to two-story buildings in the town of Tambo de Mora (measured settlements up to 0.9 m) were reported by Meneses (2008). In addition, a low intensity lateral spread failure of an embankment in the Villa area of Lima (approximately 90 km north of the rupture plane) severely damaged to the verge of collapse more than one hundred confined brick masonry houses. Estimated lateral spread was up to approximately 3.9 m (GEER 2007). Local authorities at Tambo de Mora decided to relocate the entire town to a higher ground location. Figures 2a and 2b illustrate some of the damage.

Figure 2a. Liquefaction-induced settlement of about 0.9 m of a one-story masonry house in Tambo de Mora, Peru (GEER 2007)

Figure 2b. Interior of a one-story masonry house affected by liquefaction with settlement of approximately 0.7 m. Note the completely damaged concrete slab on ground (GEER 2007)

2010 M_w 8.8 CHILE EARTHQUAKE

Several urbanized areas were strongly shaken by the February 27, 2010 M_w 8.8 Chile earthquake. Most buildings within the affected areas performed well, especially modern buildings. However, many older buildings performed poorly particularly in areas with a large concentration of unreinforced masonry and low-rise adobe construction, such as in the cities of Curico and Talca. Within the city center of Curico, where many historic adobe structures are located, nearly 90% of the structures were destroyed. Similarly, in the city of Talca, 67 km WSW of Curico, nearly every home in the city's center was severely damaged and most historic structures were flattened, whereas taller, well-designed structures appeared to perform relatively well with the exception of damage to nonstructural elements.

Liquefaction was observed to have occurred over a large area of Chile affected by the earthquake. The widespread presence of river sediments and the long duration of the event most likely contributed to the large number of observations of liquefaction (GEER, 2010). Liquefaction was observed in areas as far north as Vina Del Mar and Valparaiso, and as far south as Arauco and Lebu.

Clear evidence of soil liquefaction was observed throughout the grounds of the new Hospital Provincial in Curanilahue adjacent to the structures. This new hospital facility has 10 structurally isolated wings with heights ranging from one to six stories. The foundation is a likely common to that observed in the two-story wings, namely shallow spread and strip type construction with interconnecting grade-beams.

The top soil layer is an artificial fill of 0.7 m in thickness that contains silt, debris, and coal. Directly below the fill there is a clayey silt/sandy silt/silty clay material with a thickness of about 1.6 m, medium to high water content, low consistency, and medium to high Plasticity Index (PI). Below this layer, between depths of 2.3 m and 3.4 m, there is a silty sand and clayey gravel stratum with a thickness of about 1.1 m, high water content, low plasticity with presence of subrounded gravel particles (maximum diameter =3.8 cm), followed by a 0.8 m thick stratum of medium to high PI clayey gravel with high water content (stones with maximum size 23 cm). The last stratum identified through standard penetration test sampling (at a depth greater than 3.4 m) is composed of clayey silt with high water content, medium consistency, and high plasticity. Groundwater was measured at an average depth of 0.87 m, varying between 0.65 m and 1.60 m throughout the site.

Sediment ejecta were observed in many locations as shown in Figure 3. The ejecta appeared to range from plastic silts to low plasticity silty sands. Liquefaction-induced ground deformation caused translational movements and tilts of the building. There was also evidence of internal distortion of these structures and their foundations.

Figure 3 Sediment ejecta observed around Hospital Provincia wings (GEER, 2010)

Several up-scale homes in the northern part of Concepción were damaged by a translational landslide movement. Shallow groundwater was observed at the site near the toe of the slide. The slide appeared to be relatively shallow with its toe compressing ground in a zone that was about 8 m wide, its head scarp causing a series of parallel extension cracks over a zone that was about 11 m wide (Figure 4), and its body between the toe and head scarp showing little evidence of internal ground distortion within it (GEER, 2010). At the toe of the slide, the ground shortened about one m and pushed up about one m due to compression across a zone that was initially 8.5 m wide.

Figure 4. A damaged house located at toe of landslide (left); a damaged house located at head scarp of landslide (right) (GEER, 2010)

2010 M_w 7.2 EL MAYOR-CUCAPAH EARTHQUAKE

Liquefaction and lateral spread were widespread throughout the Mexicali Valley, Baja California, and also present in the Imperial Valley, California, at sites adjacent to bodies of water. Small town and villages located across the Mexicali Valley were seriously affected by liquefaction and ground failure, particularly one- and two-story housing. Construction materials and systems included unreinforced masonry with brick and concrete blocks, wood, and confined masonry. Hundreds of houses were subjected to large deformations induced by vertical and lateral deformations of the ground induced by liquefaction and lateral spread, and the resulting loss of bearing capacity. Even though most of the houses were so severely damaged beyond repair, total collapses of these houses were rare. This could be one of the reasons that not many casualties occurred during this event (EERI 2010; GEER 2010a). Figures 5 and 6 show liquefaction-induced damage.

Figure 5 – House affected by lateral spread in Rio Hardy, Baja California, Mexico.

Figure 6 – Settlement of approximately 1 meter in a two-story house in Oaxaca, Mexicali Valley, Baja California.

2010 M_w 7.1 DARFIELD EARTHQUAKE

During the Darfield earthquake, extensive liquefaction and associated lateral spreading occurred in various parts of Christchurch city, the town of Kaiapoi, and the beachside settlements near the Waimakariri River. It was observed that residential houses and lifeline systems were significantly damaged due to widespread liquefaction and associated lateral spreading and ground failure. An overview of the damage and performance of residential houses are presented below.

Figure 7 shows the building at St Paul's Church on the Gayhurst Road, Dallington, which was damaged due to a complex pattern of ground distortion including large cracks and vertical offsets around the building. The width of the crack ranges from 50 to 90 cm and the maximum vertical offset is about 33 cm. It was observed that widespread sand ejecta around the perimeter of the footing and backyard lawn.

Figure 7. Liquefaction-induced bearing failure at St Paul's Church (GEER, 2010b)

The geotechnical reconnaissance team (GEER, 2010b) carried out a comprehensive investigation at St Paul's Church. This site is centrally located in a meandering loop of the Avon River and bounded by the river on all sides at distances of about 150 to 250 m, except to the north/northeast. Despite being located more than 150 m from the free-face of the river, lateral spreading was observed in this area. The team performed a dynamic cone penetration test and a spectral analysis of seismic waves at the site. They found that the site consists of a non-liquefiable soil of about 2.8 m that was underlain by the liquefiable layer of about 1.2 m thick. The ground water table was reported to be about 2.3 m.

A large number of residential houses in Bexley were damaged by widespread liquefaction and associated lateral spreading. Bexley is bounded by the Avon River on the east side and by the Bexley wetland on the south side. Figure 8a shows a large ground crack due to lateral spreading at Kokopu Place. Cracks occurred in unreinforced slabs induced by lateral spread were also observed as shown in Figure 8b.

Figure 8a. Large ground cracks due to lateral spreading at Kokopu Pl (GEER, 2010b)

Figure 8b. Cracks in unreinforced slab induced by lateral spreading (GEER, 2010b)

Figure 9 shows the compromised ground support beneath the concrete slab-on-grade house foundation induced by lateral spreading. The floor slab fissure measured 5 to 7 cm wide extended through the full width of the house. The house was observed to be subject to no significant tilting despite the house being subject to settlement. No significant damage to the walls of the building was observed as well.

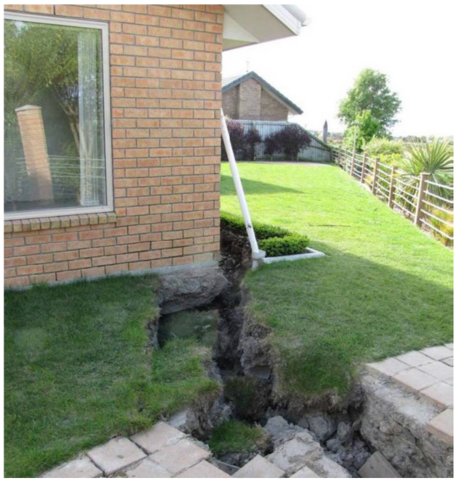

Figure 9. Lateral spreading compromising ground support beneath the concrete slab-on-grade foundation at Kokopu Street (outside of the building) (GEER, 2010b).

2011 M_w 6.1 CHRISTCHURCH EARTHQUAKE

This earthquake caused widespread liquefaction-induced and associated lateral spreading-induced damage across Christchurch, especially in the central city and eastern suburbs. A unique aspect of the earthquake is the damage exacerbated by buildings and infrastructure already being weakened by the 2010 M_w 7.1 Darfield earthquake. Due to its closer proximity to the city, the 2011 M_w 6.1 earthquake caused substantially more damage to Christchurch than the 2010 M_w 7.1 Darfield earthquake. Liquefaction was more severe in the CBD and eastern suburb as a result of stronger shaking. Liquefaction and associated lateral spreading were estimated to have severely damaged 15,000 residential structures, more than half of which beyond an economical repair.

Figure 10 shows a one-story residential house in the suburbs that was damaged by differential settlements. Liquefied foundation soils led to the loss of bearing capacity of the foundation, which further caused the separation of walls. The soils in the suburbs are predominantly loose fluvial deposits of liquefiable clean fine sands with non-plastic silt. The top 5 to 6 meters are in a very loose state with uncorrected cone penetration test tip resistance varying between 2 to 4 MPa.

Figure 10. Damage building due to differential settlement (GEER, 2011).

Liquefaction-induced punching settlements were observed to damage several buildings founded on shallow foundations located within the liquefied zone. Figure 11 illustrates one example of punching settlements of the structure. This structure is a two-story industrial building. It was observed that the continuous sand ejecta around the perimeter of the footing and signs of punching shear failure mechanism. The building settled about 25 cm with respect to a fence at its southeast corner and settled about 10 to 20 cm relative to the ground at its northwest corner.

Figure 11. A two-story building subject to liquefaction-induced punching settlements (GEER, 2011)

Figure 12 shows a three-story building supported on shallow foundations that settled at its front (i.e., north), which created large differential settlements. The building was tilted about 2 degrees by the differential settlements. The building was also uniformly displaced laterally about 15cm toward the area of the significant liquefaction near the front of the building. A large volume of sand ejecta was observed at the front part of the building. Ground tension cracks were also observed to propagate east and south of the building, which agree with the observed lateral movement of the building toward the north.

Figure 12. A three-story building subject to liquefaction-induced differential settlement and sliding (GEER, 2011)

After the 2010 Darfield earthquake and prior to the 2011 Christchurch earthquake, the Preparatory School building at St Andrews School was demolished and renovated. A new two-story structure was built on the 18 m deep screw piles. The building was connected to two existing buildings that are supported on shallow raft foundations. The portion of the structure on the shallow raft foundation moved away from the pile supported portion by about 20 cm and settled about 20cm, while the pile supported portion of the structure remained in place and the surrounding ground settled up to 25 cm. Figure 13 shows the layout of the Preparatory School and measured ground settlements relative to the structure.

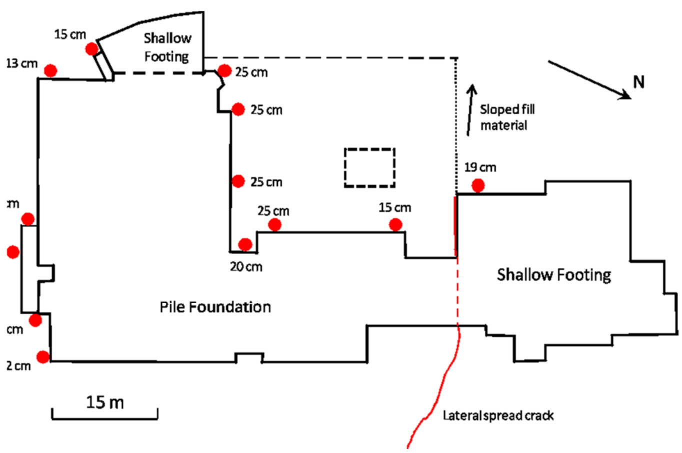

Figure 13. Layout of the Preparatory School and measured ground settlements relative to the structure (GEER, 2011)

2011 M_w 9.0 GREAT EAST JAPAN EARTHQUAKE

Extensive soil liquefaction and instances of lateral spread occurred along the coast of Tokyo Bay and around Tonegawa River floodplain. Tokimatsu et al. (2012) reported that liquefaction mainly occurred within relatively new reclaimed area, with liquefaction-induced settlements up to 0.6 m resulting in tilt and vertical movements of wooden and reinforced concrete buildings with spread foundations. Tokimatsu et al. (2012) also noted that buildings with spread foundations with large rigidity, such a mat foundations, did not experience significant structural damage to the superstructures; however these buildings either tilted or settled.

Urayasu city is a fancy residential area conveniently located with easy and fast access to Tokyo downtown. Approximately 80 percent of the city area was affected by liquefaction resulting in serious damage to buildings and lifelines (water, sewage, electricity). Most of the city was built on an artificial island, reclaimed land, and areas that were not affected were because ground was improved either by using sand compaction piles and gravel drains. In reclaimed unimproved areas, boiled sand, ground subsidence, titling and sinking of wooden houses were observed. Structural damage induced by strong ground shaking was rarely observed (Katsumata and Tokimatsu 2012).

Tsukamoto et al. (2012) summarized that tens of thousands of residential houses were subjected to liquefaction-induced settlement and tilting at areas such as reclaimed areas at Urayasu and Chiba cities along the Tokyo Bay; Katori City, Chiba Prefecture and Itako, Kamisu and Kashima cities, Ibaraki Prefecture, located along the lower stream of Tonegawa River.

Towhata et al. (2011) reported that residents of affected houses were annoyed by dizziness and headaches by tilting of the houses as small as one percent or less of floor inclination. Also Towhata et al. (2011) pointed out that restoration of houses with no serious structural damage could be restored by leveling out the foundation; however these procedures could not be cost-effective for homeowners. One of the reasons could be that current technologies to improve ground under existing buildings like houses that are less strong than reinforced concrete buildings, special care and experience are indispensable.

DISCUSSION

Lightweight structures such as 1- or 2-story residential buildings have short fundamental periods of vibration; i.e. 0.1 to 0.3 seconds. Youd and Carter (2005) studied the influence of soil softening and liquefaction on spectral accelerations and found that softening and liquefaction did not lead to amplification of spectral accelerations for fundamental periods less than one second. International Building Code (2012) does not recommend performing a site-specific site response analysis if a building on liquefiable sites has a period less than 0.5 seconds. Hence after reviewing case histories of lightweight structures and the liquefaction-induced damage, it would be reasonable to state that the damage is not caused by inertial forces but by the ground failure and the associated consequences, including vertical and lateral movement of the ground, and bearing capacity failure.

Elgamal et al. (2005) studied liquefaction-induced settlement of shallow foundations and some remediation techniques by 3D numerical simulation. They explored the influence of compaction and/or increased drainage on the liquefaction-induced settlement below an applied surface load, and concluded that high drainage was effective in reducing settlement. However they concluded that a more accurate simulation of liquefaction-induced compaction and densification requires still further research.

Towhata (2007) in discussing liquefaction-induced damage to private houses in Japan acknowledges that the major issue is the limited income and budget available for liquefaction mitigation measures. Towhata (2007) reports that after the 2000 Tottoriken Seibu earthquake, private houses damaged by liquefaction tilted and experienced significant differential settlements, and angular distortions as small as 1/700 made residents very uncomfortable. Asada (1998) concluded, after studying the damages to 938 houses after the 1983 Nihonkai-chubu earthquake, that 55 percent of the houses were damaged by liquefaction. Also Asada (1998) realized that most damages were caused when the ground water table was shallow, less than 2 m below ground surface. Towhata (2007) suggests a correlation between differential subsidence of buildings and buoyancy. After discussing an analogy of buoyancy force, he concludes that settlement of buildings on liquefied ground is at least qualitatively governed by gravity and buoyancy.

Dashti et al. (2010) using centrifuge experiments studied the mechanisms of seismically induced settlements of buildings with shallow foundations on liquefiable soils. They found that seismic liquefaction-induced settlements occurred within a building footprint are completely different and larger than the post-liquefaction reconsolidation settlement in the free field, which is typically estimated using procedures developed by Tokimatsu and Seed (1987), Ishihara and Yoshimine (1992) and Wu et al. (2003). After measuring building settlements in the centrifuge experiments, Dashti et al. (2010) concluded that most building settlements were caused by static and dynamic deviatoric-induced movements in combination with sedimentation and localized volumetric strains due to partial drainage during earthquake shaking. In addition they concluded that it is still needed an advanced understanding of the liquefaction-induced building settlement mechanisms to develop improved numerical simulations, design engineering procedures and propose mitigation techniques to minimize settlements.

On the other hand, not only current practice uses estimation of liquefaction-induced settlements in the free-field but also estimation of liquefaction potential is performed in the free-field. Rollins and Seed (1990) using available case histories, shake table tests, and centrifuge tests studied the influence of buildings on liquefaction potential evaluation and building damage. They concluded that sands deposits bellow short-period, low-rise structures appear to have higher potential for liquefaction than predicted by simplified methods.

CONCLUSIONS AND RECOMMENDATIONS

A review of case histories of liquefaction-induced foundation failures of lightweight structures (particularly 1- and 2-story residential buildings) and pertinent literature lead us to conclude:

1) Liquefaction-induced building settlements up to approximately one meter have been observed;
2) Most lightweight buildings were severely damaged even to the verge of total collapse but the cases of total collapse were rare. Most buildings had to be demolished after the earthquake;
3) Buildings with relatively stiff foundations experienced tilting and inclination of the floor even in small amounts that made buildings inhabitable;
4) Tilted surviving buildings needed repair that required sophisticated and expensive techniques, not reasonable for this type of buildings;
5) Even though there is some progress, current knowledge of liquefaction-induced building settlements mechanisms and liquefaction potential evaluation under buildings is poor or incipient. Until this knowledge is not improved, design of cost-effective mitigation techniques is not feasible.
6) Current techniques of foundation strengthening or pile foundations and/or ground improvement that could be suitable for important structures are not suitable for lightweight buildings (1- or 2-story buildings) from a technical perspective and from an economic point of view. Foundation would be much more expensive than building itself. This would not make sense for a homeowner for example.

Based on these conclusions we recommend:

1) Avoid construction of residential areas in potentially liquefiable soil deposits;
2) Owners of lightweight structures on potentially liquefiable soil deposits should be aware of the potential foundation failures that can cause near collapse or total loss of functionality;
3) Owners should be aware that current ground improvement techniques to mitigate liquefaction are costly and cannot be justified for lightweight structures; i.e., cost of ground improvement more expensive than cost of structure.

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