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Over-turning of a building with pile foundation - combined effect of liquefaction and tsunami

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ABSTRACT

After the 2011 off the Pacific-coast of Tohoku, Japan, earthquake, steel-frame and reinforced concrete buildings supported by the pile foundation were found to be collapsed in Onagawa town, Miyagi prefecture. One of their piles located near to the coastline was hanging from the footing of the overturned building. This fact may suggest some combined mechanisms of liquefaction and tsunami on their failure. In this study, the combined effect on stability of such a building is investigated by centrifuge and numerical simulations. Centrifuge test results show that the building collapsed by the tsunami attack during liquefaction. Results of the subsequently conducted effective stress analysis also suggest such a failure mechanism. It is concluded that, in reality, pile supported buildings might be survived liquefaction due to strong shaking, however, combined action with a tsunami triggered their failures.

Introduction

The 2011, off the pacific coast of Tohoku, Japan, earthquake

The great Tohoku, Japan, earthquake (M_w 9.0) of March 11, 2011 struck the breadth Japan between Tohoku (in the north-east) and the Kanto Plain. The rupture area was estimated to be approximately 450 km x 200 km off the Pacific coast of Tohoku, Japan (Stewart et al. 2013), and generated a tsunami that struck the area from Hokkaido to Kyushu (Mori et al. 2013). The major cause of death was direct action of the tsunami with most fatalities occurring in the Tohoku region. Along the east-coast of the Tohoku district, the tsunami took 15,883 lives with 2,761 still missing as of June 6, 2013 (National Police Agency 2013). The number of totally and partially damaged buildings was, respectively, 128,530 and 230,332, and more than 200 bridges collapsed (Akiyama et al. 2013). The estimated cost of direct damages was 16.9 trillion JPY (US$211 billion). A large number of geotechnical structures were damaged, including embankments and dams, and large ground deformations due to liquefaction were observed (Kazama & Noda 2012). Among them, off-shore tsunami breakwaters constructed at the bay mouths in the Tohoku region were damaged due to the tsunami. For their damage mechanism, it was suggested that seepage in the rubble mound caused by the difference of water head in front and at the back of a caisson, which was not considered in its design, may trigger loss of bearing capacity of the rubble mound (Tobita and Iai, 2014; Takahashi, et al. 2014).

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Mechanism of overturning of pile supported buildings

In Onagawa town (Fig. 1), Miyagi prefecture, the tsunami reached 15 m in height and surged 1 km in-land. The tsunami first damaged the town center, and then spread along two major valleys of late Pleistocene and Holocene marine and non-marine deposits, leaving over 1,000 missing and 300 confirmed dead (Konagai et al. 2011). In this town, RC and steel-frame buildings with pre-stressed high-strength concrete piles were overturned in several locations. The typical damage pattern on buildings with piled foundations was for piles to be cut near the pile head, and buildings then possibly floated and/or pushed inland for overturning (Tamura 2012). Although the seismic capacity of buildings has been significantly increased after 1981 when the new version of the seismic design code was adopted, the seismic design of piled foundations was not enforced then and their capacity was determined solely using vertical loads. Therefore it is possible to say that damaged pile-supported buildings are likely to have been constructed before 1984 when the earthquake-resistant design of piled foundations was recommended. It was enforced by the law in 2001 (Tamura 2012).

In the present study, the mechanism of overturning of pile supported buildings was investigated through centrifuge experiments and numerical analysis. In Onagawa town, one steel-framed building was overturned with one of its piles still attached to the footing. (Fig. 2) (Konagai et al. 2011). The cause of damage was speculated as combined effects of the tsunami and softening of the ground due to liquefaction, although the site was washed by the tsunami and very little evidence of liquefaction remained. The failure mechanism of pile supported buildings may be thought of as (1) loss of bearing capacity, (2) loss of lateral resistance and skin friction of piles due to liquefaction, then (3) deformation of the ground due to the hydrostatic and hydrodynamic force of the tsunami, and (4) buoyant and thrust forces acting on a side of the building.

Figure 1. Aerial view of Onagawa town, Miyagi Pref (google map).

Figure 2. Overturned steel-frame building (Eshima Kyosai Kaikan) (Konagai et al. 2011).

Centrifuge studies and damage mechanism

Centrifuge tests were conducted under 20 g with a 1/200 scaled model by applying the generalized scaling law (μ = 10 and η = 20) (Iai et al. 2005; Tobita et al. 2011, 2012). A soil box with a water tank and movable gate was installed and used to generate a tsunami for the scaled model (Fig. 3). As shown in Fig. 3, the moveable gate, which was a small vertical wall closing an opening located at the bottom of the water tank and connected to the air piston, could be slid laterally using air pressure to release the water in the tank from the gap between the gate and a fixed lateral wall. At the exit of the gate, a punched metal plate with 3 mm openings was attached to modify the water flow. Once the water was released from the tank, it flowed across the sand box where the model structure was placed, then it was captured in the drainage tank attached at the base of the box (not shown in Fig. 3) to eliminate wave reflections generated by the opposite side wall.

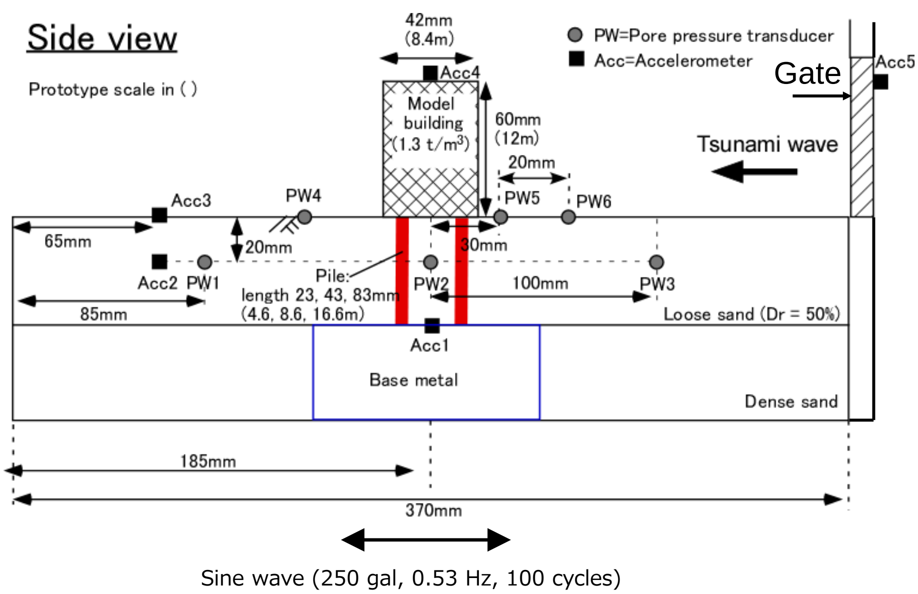


Figure 3. Schematic view of the model ground and pile-supported building.

Table 1. Test cases

Case	Thickness of liquefiable layer (m)	Excess pore water pressure when tsunami attacks
1-1	8.60	Yes
1-2	8.60	No
2-1	4.60	Yes
2-2	4.60	No
3-1	16.6	Yes
3-2	16.6	No

The material used in the dense (Dr = 90%) and loose sand (Dr = 50%) layers was No. 7 silica sand (D_{50} = 0.13 mm). Six pore water pressure transducers were installed to measure the excess pore water pressure in the ground (PW1-PW3) and tsunami height at the ground surface (PW4-PW6), and six accelerometers were installed at the locations shown in Fig. 3.

In reality, the tsunami height of the 1st arrival wave observed at the Onagawa nuclear power plant was 10 to 15 m and took about 900 sec (15 min) to reach the maximum, while in the model, as shown later, due to limitations of the device, it took only 150 sec to reach the maximum.

In total 6 tests were conducted by varying the thickness of liquefiable layer and timing of tsunami arrival (Table 1) to be either during liquefaction or after complete dissipation of the excess pore water pressure. The pile length was adjusted so that the thickness of the liquefiable layer and the pile length were taken to be equal in order to simulate pile break at the boundary of dense and loose layers.

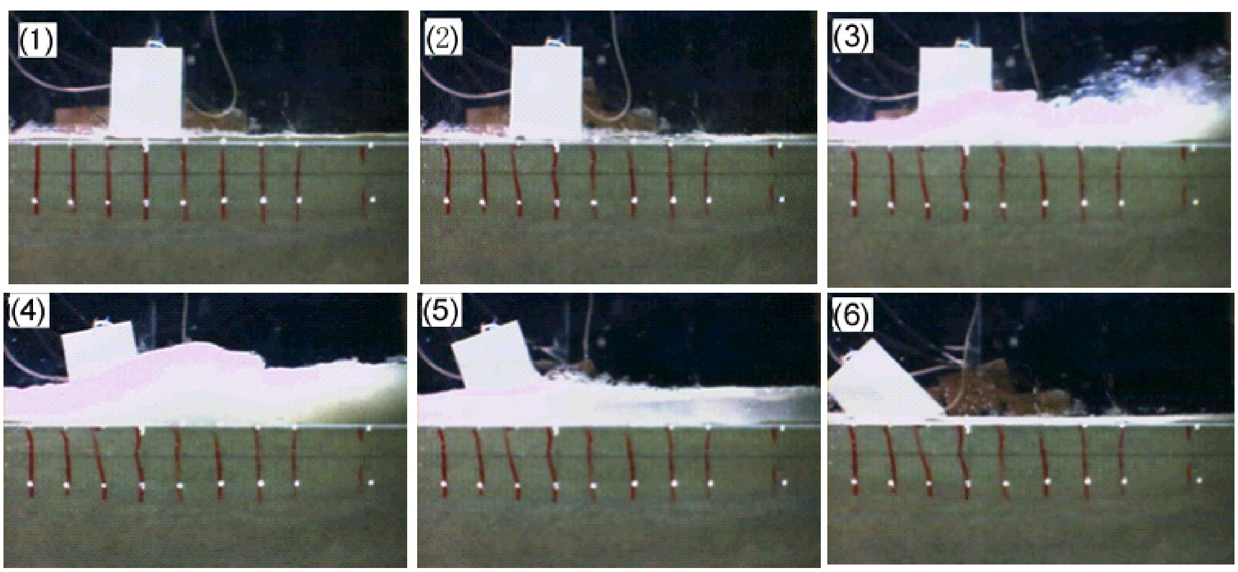
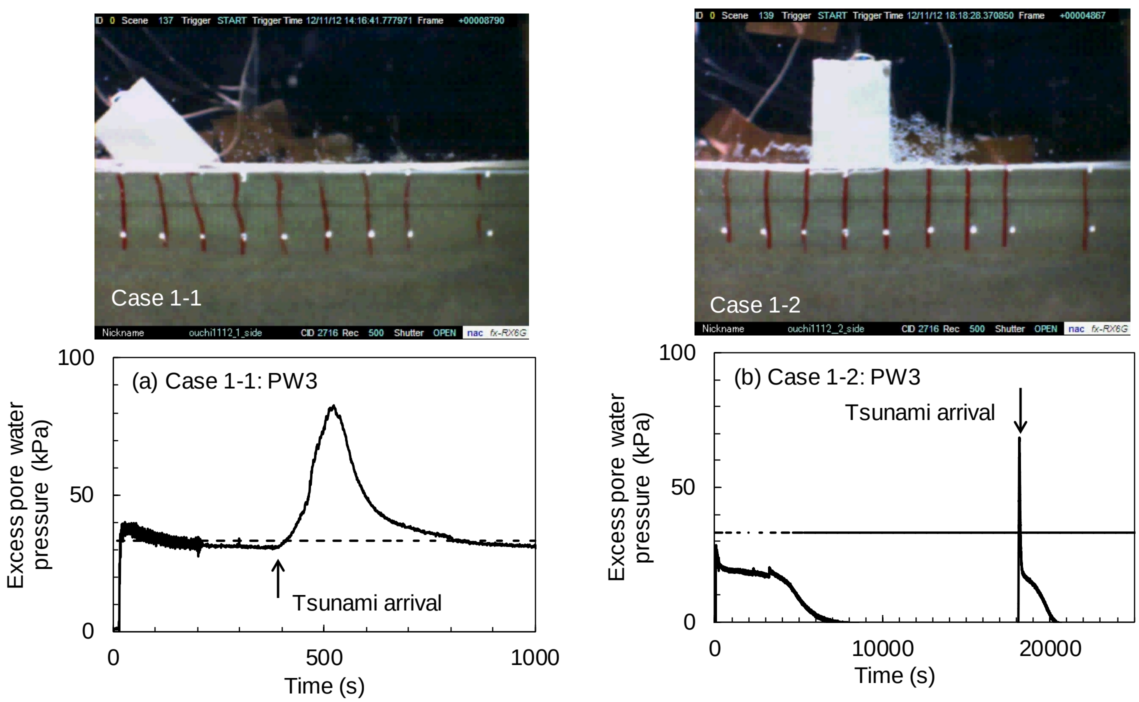


Figure 4. Sequence of overturning of the model building (Case1-1).

As an example, the sequence of overturning of the model building for Case 1-1 is shown in Fig. 4. In Case 1-1, tsunami arrival was just after shaking, when the excess pore water pressure was still high, i.e. the ground was under liquefaction. As shown in Fig. 4(1) to 4(3), the building sustained shaking. However, in Fig. 4(4), when the maximum height of the tsunami was observed, the building started to tilt and remained permanently inclined [Fig. 4(6)].

In the centrifuge tests, the timing of tsunami arrival played a dominant role in the failure of the model building. As shown in Figure 5(a) for Case 1-1 and Fig. 5(b) for Case 1-2, when the tsunami hit the building during liquefaction, as shown in the time history of excess pore water pressure buildup (measured at PW3 in Fig. 3) in the bottom figure of Fig. 5(a), it tilted (Case 1-1), while it did not tilt if the tsunami arrived after complete dissipation of the excess pore water pressure in the ground. Considering that the strength of the ground during liquefaction is extremely small, the result seems to be quite reasonable and agrees with the speculations above.



(a) Case 1-1 (b)Case 1-2

Figure 5. Effect of liquefaction on the overturning of the model building due to tsunami: (a) Case 1-1: with liquefaction and (b) Case 1-2: without liquefaction.

Then, the effect of the thickness of the liquefiable layer was investigated to confirm whether the loss of lateral resistance of piled foundations, which is dependent on pile length, had significant impact on the stability of a model building. To take into account the pile break at the boundary of the loose and dense sand layers, the pile length was kept at the same length as the thickness of the loose liquefiable layer. As shown in Fig. 6, the shorter is the pile length, the larger is the inclination of the building. Thus, it confirmed that a loss of lateral resistance of piled foundations caused overturning of a model building.

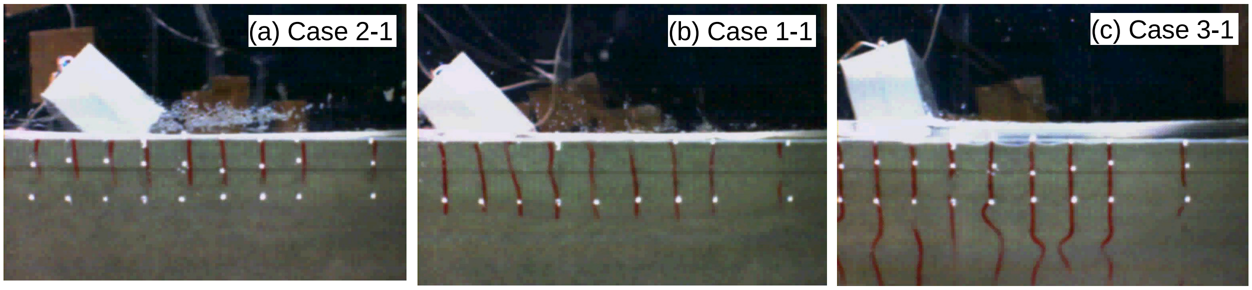


Figure 6. Overturning of a model building: (a) Case 2-1: thickness of the liquefiable layer (=pile length) 4.6 m, (b) Case 1-1: 8.6 m (c) Case 3-1: 16.6 m.

Numerical analysis

To visualize the stress distribution in the ground near the building, effective stress analysis was conducted using FLIP/TULIP (Ver.6.1.0) (Iai et al. 2013a 2013b, Iai et al. 2013c). In the analysis, the multi-spring element (Cocktail glass model) was implemented as an elasto-plastic constitutive relationship of soil. In the analysis, the model parameters shown in Table 2 to Table 5 were adopted. The prototype used in the centrifuge experiment was analyzed as shown in Fig. 7. Because the numerical method adopted in the study has no option to simulate water flow such as a tsunami, the hydrostatic force converted from tsunami height (6.0 m) was applied (Fig. 7). The thrust force applied on the side of the caisson corresponds to the hydrostatic force determined by assuming 3 times the water depth due to the tsunami (OCDI 2009). The hydrostatic force corresponding to a water depth of 6 m was u at the surface of the sea facing section. Using this method, ground water flow could be simulated. In the analysis, the forces shown in Fig. 7 were gradually increased to simulate the arrival of the tsunami. As a result, shown in Fig. 8, the sea facing side settled while the inland facing side uplifted due to ground water flow, and the building was tilted as indicated in the figure.

Table 2. Model parameters for sand.

Material	Density	Permeability	Shear modulus	Bulk modulus	Friction angle
	t/m^3	m/s	kPa	kPa	deg.
Loose sand	1.85	1.46x10^{-4}	5.57x10^4	1.45x10^5	38.5
Dense sand	1.94	1.00x10^{-8}	1.25x10^5	3.26x10^5	30.0

Table 3. Model parameters of the elastic plane element for the building.

Young's modulus	Poisson ratio	Density
kPa		t/m^3
3.14x10^{10}	0.30	1.3

Table 4. Model parameters of the beam element for piles.

Outer diameter	Density	Shear modulus	Poisson ratio
m	t/m3	kPa	
1.2	7.93	7.40x108	0.30

Table 5. Model parameters of the joint element.

	Stiffness		Friction angle
	Normal	Tangential	
	kPa/m	kPa/m	deg.
Base	1.0×10^4	1.0×10^4	31
Pile	1.5×10^8	0.0	0.0

Contours showing excess pore water pressure ratios in the ground before application of the tsunami [Fig. 9(a)] indicate that the surrounding ground was totally liquefied. As time passed and thrust force due to the tsunami increased [Fig. 9(b)], the excess pore water pressure close to the building decreased, especially on the inland side, because of large shear strains associated with deformation of the building. The excess pore water pressure ratio under the building on the sea side markedly increased [Fig. 9(c)] because of the uplift of the foundation associated with rotation of the building. This implies that the ground near the surface under the building was kept liquefied and, therefore, became vulnerable to scouring.

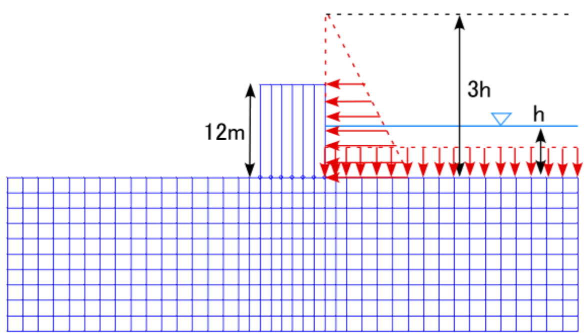


Figure 7. Finite element mesh and assumed distributed force due to tsunami.

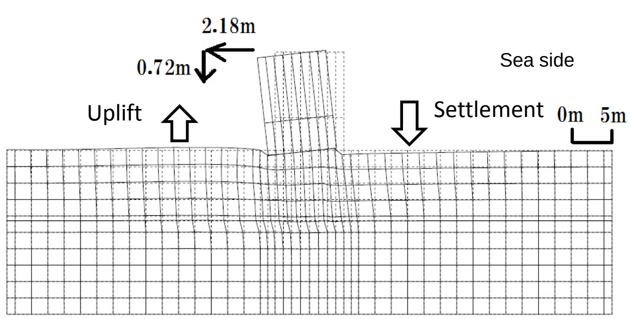


Figure 8. Before and after deformation

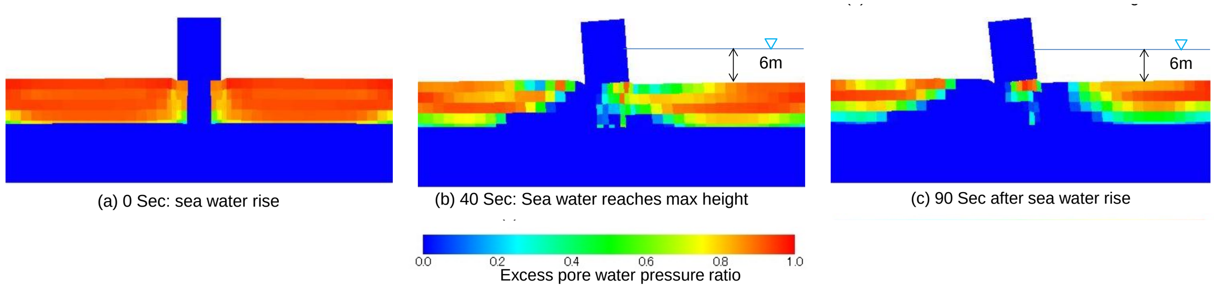


Figure 9. Deformation and distribution of the excess pore water pressure ratio.

Conclusions

Steel-framed and reinforced concrete buildings, which had been thought of as relatively safe structures with respect to tsunamis, collapsed in Onagawa town, Miyagi prefecture. It was reported that one of their piles hung from the foundation of an overturned building. This suggested that the combined action of liquefaction and the tsunami triggered the collapse of the building. Results of centrifuge tests showed that the model building collapsed when the tsunami attacked during a period of high excess pore water pressure. In addition, the effect of the thickness of the liquefiable layer was investigated to understand if the loss of lateral resistance of the pile foundation, which is dependent on the pile length, had a significant impact on the stability of a model building. To take into account the pile break at the boundary between the loose and dense sand layers, the pile length was kept the same length as the thickness of loose liquefiable layer. Results indicated that for shorter piles (corresponding to shallow depths of liquefiable soil), inclination of the building increased. Thus, it was confirmed that loss of lateral resistance of piled foundations causes overturning of a model building.

Results of the numerical analysis indicated that the excess pore water pressure ratio under the building markedly increased on the sea facing side because of uplift of the foundation associated with rotation of the building. This implies that the ground near the surface under the building remained liquefied and, therefore, became vulnerable to scouring.

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