RECONNAISSANCE REPORT ON STRUCTURAL AND GEOTECHNICAL ASPECTS OF DAMAGES IN A RECENT EARTHQUAKE IN JAPAN

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ABSTRACT:
This paper outlines the geotechnical and structural hazards brought by the 2007 Niigataken Chuetsu-oki earthquake that occurred in the Niigata and Nagano prefecture, Japan on July 16th, 2007 (JST). The quake brought heavy damages to many wooden residential houses and traditional wooden buildings. This paper is a report of preliminary joint investigation on the structural and geotechnical aspects of the damages. Ground vibration and ground deformation were found to be the main cause that led to damages to low earthquake resistant buildings and other associated damages during the earthquake.

KEYWORDS:
Earthquake resistance, Ground deformation, Lateral flow, Liquefaction, Subsidence, Vibration characteristics

1. INTRODUCTION

On July 16th, 2007 (JST), an earthquake of magnitude 6.8 (as reported by Japan Meteorological Agency) occurred in the Niigata and Nagano prefecture, Japan. The earthquake, named the 2007 Niigataken Chuetsu-oki Earthquake, was an inland earthquake caused by reverse fault mechanism. The epicenter of the earthquake was off the Chuetsu area of Niigata Prefecture at a depth of 17 km. The greatest seismic intensity observed was 6 strong (Japanese Seismic Intensity Standard) in Niigata and Nagano Prefectures. Many lifeline utilities, houses, slopes and harbors were damaged during the earthquake. Heavy damages to many wooden residential houses and traditional wooden buildings such as shrines and temples were particularly evident during the earthquake. This paper is a report of the preliminary joint investigation by a group of academia and public sector research institute in Japan on the structural and geotechnical aspects of the damages. Nevertheless, this paper also does reflect the opinion of some of the recent reports by various other organizations in Japan.

2. OUTLINE OF THE EARTHQUAKE AND SEISMIC DATA

Figure 1 is the topographical map showing the intensity (scale 0-7) of the earthquake at various locations around the epicenter (http://unit.aist.go.jp). Kashiwazaki city and Kariwa village were the worst affected regions during the earthquake. There were several earthquake observation stations near the damaged area developed by JMA (Japan Meteorological Agency) and NIED (National Research Institute for Earth Science and Disaster Prevention). Both systems consist of a single 3-dimensional accelerometer on the ground surface. The acceleration records of the Kashiwazaki K-NET seismological station (NIG018) maintained by NIED are shown Figure 2. The acceleration response spectra (at various damping ratio, H) are shown in Figure 3, which display a predominant frequency between 0.4 and 0.5 Hz.

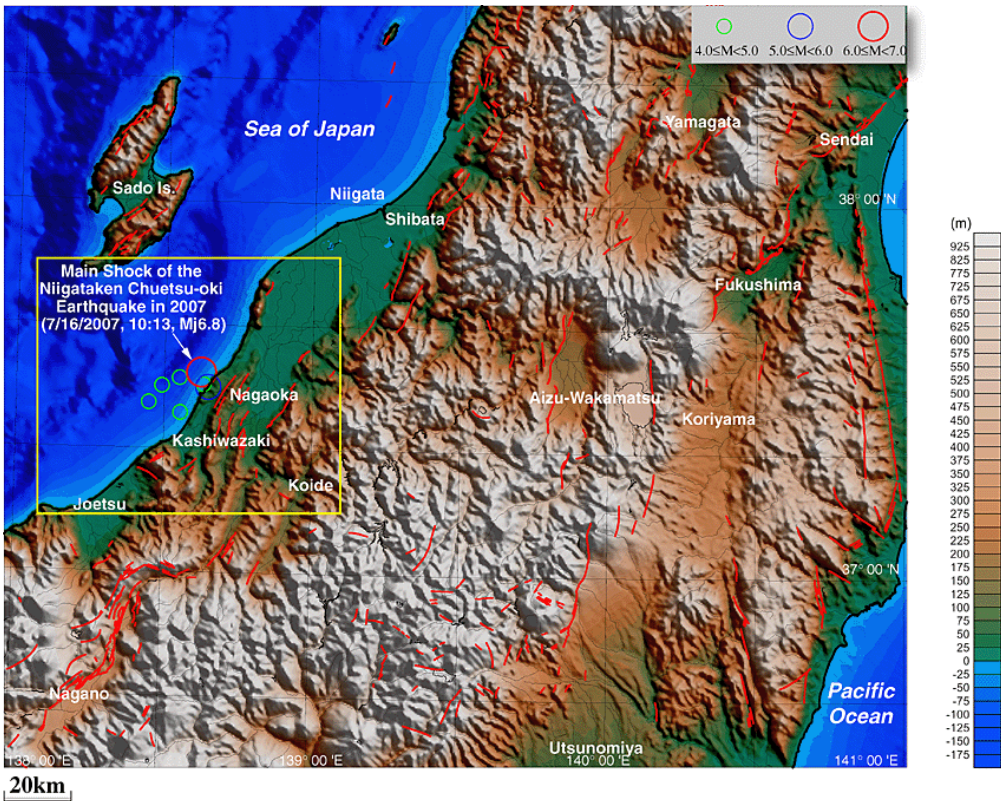

Figure 1. Topographical map showing the epicentral region (Source: http://unit.aist.go.jp)

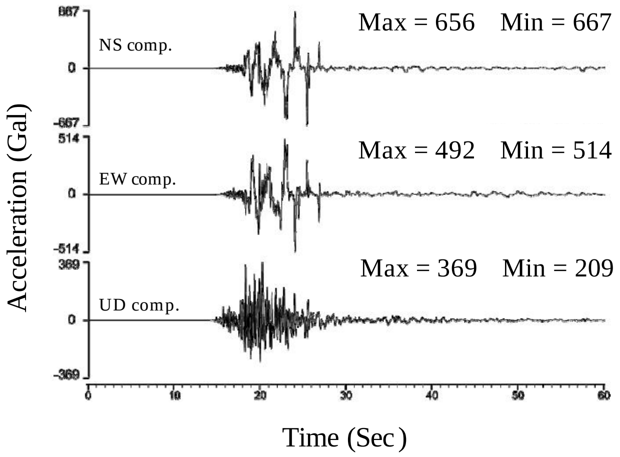

Figure 2. Acceleration ground motion recorded at Kashiwazaki K-NET station (NIG018)

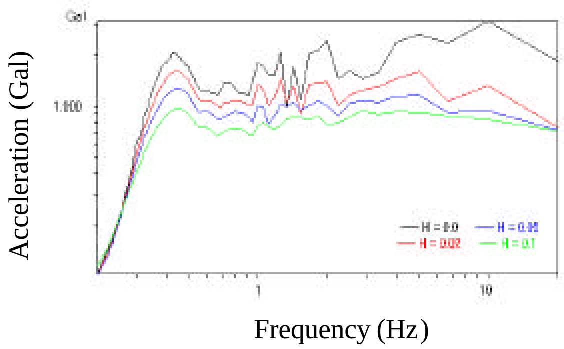

Figure 3. Response spectra

Geologically the wide area around Kariwa Village is comprised of tertiary Teradomari formation, Shiiya formation and Nishiyama formation extending along the north-northeast direction and the south-southwest direction. The geology consists of the alternate rock layer of mudstone or mudstone combined with sandstone. On the other hand, the area encompassing the city center of Kashiwazaki City is comprised of the soft alluvial deposit formed by sand and silt that had accumulated in the downstream areas of the Uh river, Sabaishi river and Betsuyama River. The long and thin shoreline comprised of the Arahama sand dunes. Furthermore, hard volcanic conglomerate and igneous rock are widely spread over the area encompassed by the Yoneyama mountain range southwest of the region.

3. INVESTIGATION OF THE STRUCTURAL DAMAGE

The major cause of the damages to structures by that earthquake can be attributed either to strong ground vibration or to ground deformation. Damages due to ground vibration were concentrated mainly to extremely low earthquake-resistant parts of the buildings (mud walls, tiled roofs, clay sheathing, poorly attached joints, foundations, barns, decayed parts). Damages due to ground deformation were observed in some newly built buildings, resulting from soil liquefaction and associated ground subsidence and lateral flow.

3.1. Damages to wooden structures

Figure 4 shows some of the damages to wooden residential and commercial houses. Damage was particularly observed in those structures that have exceptionally low earthquake-resistance combined with insufficient or poor structural conditions. These factors, added with their failure to conform to the requirements of the Building Standard Law of Japan, have led to such devastating damages. Many Shops and residential houses that lacked earthquake resistance in their store fronts/doorways collapsed towards their front. Buildings lacking of resistant walls along with poor joints and heavily decayed parts, were completely destroyed by the strong ground vibration.

Figure 4. Damages to wooden residential and commercial buildings

3.2. Damages to traditional wooden architectures

Japan's Hokuriku region is well known for its abundance of Buddhist temples. Niigata Prefecture also boasts of the largest number of Shinto shrines in Japan. As a result of this earthquake, many traditional wooden buildings such as shrines and temples, were heavily damaged. According to the statistics on damages to shrines compiled by Niigata Prefecture's Association of Shinto Shrines (2007), 75 major shrines suffered total or half destruction, 102 shrines suffered moderate damage and/or destruction, and 309 shrines suffered loss of properties.

The worst affected amongst the traditional structures was the Monkoji Temple (Figure 5) recognized by the city government of Kashiwazaki as architectural heritage. The temple, located at Nishi-Honcho of Kashiwazaki City. was completed in 1930. In 1955 roof of the main temple was changed from copper plates to tiles. The 2004 Niigataken Chuetsu Earthquake (M=6.8) brought some moderate damages to the temple, and, therefore, the roof tiles of the temple were replaced 3 years ago (after the earthquake). The salient features of the temple are the western-style large-span roof frame and less no. of pillars used in the inner temple and prayer hall. The fired clay roof tiling contained no clay sheathing. The 2007 earthquake resulted in the complete collapse and destruction of the main temple (Figure 6).

Figure 5. Monkoji temple
(before the damage)

Figure 6. Damages to wooden traditional structure (Monkoji temple)

3.3. Damages to RC buildings

There were also many instances of low-rise buildings constructed prior to 1981 suffering large deformation, bending and failure of bracing, and heavy damage to the columns. In some old buildings, there were examples in which the exterior materials such as lath mortar fell off (Figure 7). The Aqua Park building of Kashiwazaki City suffered damages due to ground deformation, which will be discussed in section 4.

In the 2004 Niigataken Chuetsu Earthquake partial damages were inflicted on Shimo-Oguni Elementary School, Nagaoka City. However, no earthquake resistant reinforcements measures were taken following the earthquake, and thus, the school suffered serious damages in the 2007 Niigataken Chuetsu-oki earthquake. On the other hand, a school building that recorded severe damages during the 2004 Niigataken Chuetsu Earthquake and were reinforced against earthquake (Oguni Junior High School, Nagaoka City), was completely intact during the earthquake in 2007. Oguni Junior High School had 2 buildings with RC structures, one rebuilt after its total destruction in 2004, and another reinforced after suffering mid-level damages.

Bracing of a gymnasium, designated as the district evacuation center (built in 1993), incurred damages during the 2007 earthquake. There were instances of anchor bolts coming out of the connecting joints of steel and RC columns. The building suffered damages during the 2004 Niigataken Chuetsu Earthquake and repairing works were undertaken. Therefore, determining the cause of damage of this building in the 2007 earthquake, needs detailed and further investigation.

Figure 7. Damages to RC structures

3.4. Relation between the damage and the ground vibration characteristics

According to the criteria proposed by Kawase (1998), earthquake ground motions with PGA larger than 800 Gal and PGV larger than 100 kine would produce severe damages on structures. The pairs of values (PGA vs. PGV) of some of the large earthquakes in Japan since the 1995 Hyogo-ken Nanbu Earthquake are plotted in Figure 8. In the Figure, encircled numbers (①-⑰) represent various earthquake records. Numbers ⑯ and ⑰ represent the records of K-NET station at Kashiwazaki and Ojiya during the 2007 Niigataken Chuetsu-oki Earthquake. In the Figure, dashed lines show the equivalent predominant frequency (EPF), whose relation is given in Eq. (3.1).

$$EPF = PGA / (PGV \times 2\pi) \quad \text{(Hz)} \qquad (3.1)$$

Applying the values of PGA and PGV recorded at the K-NET recording station installed at Kashiwazaki (NIG018) in Eq. (3.1), a value of about 1.02 Hz is obtained for EPF (number ⑯ shown in red in Figure 8). Location of number ⑯ lies in the pink area, indicating the reasons for the rampant damages on buildings near this earthquake observation site. However, this value of EPF is not concordant with the predominant frequency (0.4 – 0.5 Hz) obtained in Figure 3. This implies a strong non-linear behavior of the ground.

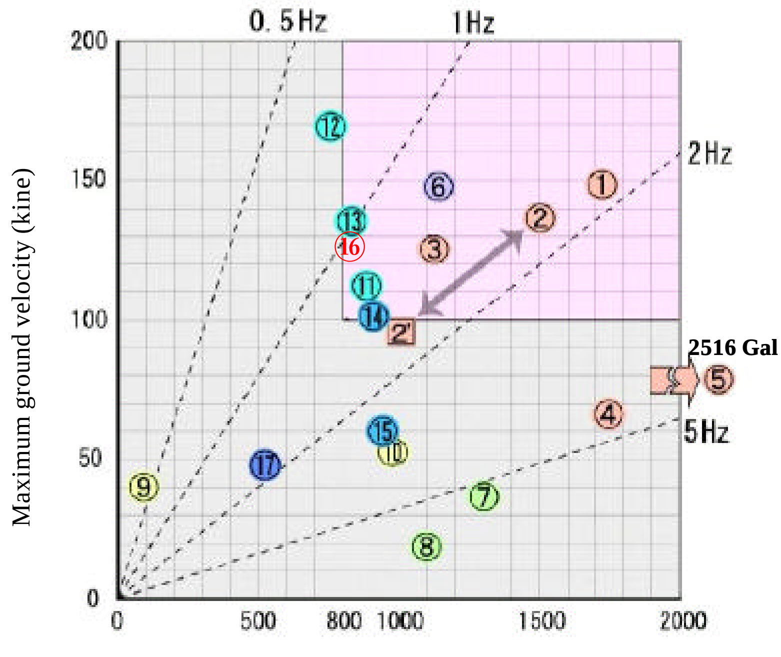

Figure 8. Criteria for estimating severe damages on structures based on PGA and PGV (After NEID , 2007)

Thus, a comparison between the values of predominant frequencies in acceleration response spectrum of strong ground motion and the values of equivalent predominant frequency (EPF) could yield a good clue to strong non-linear behavior of the ground. Analyses of the H/V spectra of many observed motions during the earthquake show that the predominant periods of the weakest motion and the strongest motion were not the same, and the stronger period's predominant period had developed into a long period component (JSCE, 2007). Each of the observation station contained sand layers with small N-values in the upper layer (Niigata Prefecture, 2002), and therefore, influence of a non-linear response during strong vibration cannot be ruled out.

The above damages reveal that the majority of buildings which strictly complied with the Building Standard Law of Japan, along with the earthquake resistant buildings did not record any serious damages. Amongst the damaged buildings, damages were recorded to those parts of the buildings that have exceptionally low earthquake-resistance such as mud walls, tiled roofs, clay sheathing, joints, etc. It was found that they fail to satisfy the requirements of the Building Standard Law of Japan. Damages in the newly built buildings, which either tilted or developed cracked, were due to soil liquefaction and lateral displacement. Detailed damages from liquefaction and related phenomenon are described in the following section.

4. DAMAGES RESULTING FROM LIQUEFACTION AND GROUND DEFORMATION

The occurrence of liquefaction was extensive around Kashiwazaki city and Kariwa village. Liquefaction was found to be concentrated on relatively young deposits mostly consisting of sand or silty sand layers or quaternary sedimentary layers, such as the skirts of sand dunes or former river channel areas. As a result, in the areas adjacent to these, many slopes and embankments collapsed and the buildings experienced large ground subsidence and lateral displacement. According to a report compiled by Wakamatsu (1992), the 1964 Niigata Earthquake and the 2004 Niigataken Chuetsu Earthquake also reported similar damage due to liquefaction in various locations including Kariwa Village.

4.1. Damages to railway station

In the Arahama district of Kariwa Village (areas in the vicinity of JR Echigo Line's Arahama Station), many sand boilings indicating liquefaction and resulting ground subsidence were observed. Figure 9 shows such occurrence of sand boilings around Arahama Station. The fluvial deposits in that area were predominantly comprised of fine sand containing few fine-grain particles. The ground suffered large subsidence (approximately 2~5 cm) due to liquefaction, but did not cause damages to houses nearby. Cracking in the platform of Arahama Station and bending of the rail tracks were the results of the lateral flow due to liquefaction.

4.2 Liquefaction induced slope failures and building damages

In the Inaba district of Kariwa village (adjacent to JR Echigo Line's Kariwa Station), a relatively large area of Arahama sand dunes were liquefied, leading to the collapse of several slopes. Figure 10 shows such collapse of slopes. About 20 m of slope failures were observed. The relatively low-density slope collapsed into an arc-shape, and the debris reached the neighboring houses and causing damage to the houses (Figure 11). According local eyewitness, a fountain of water reaching about 1 m in height occurred. This implies that the underground water level was higher than usual during the earthquake.

Figure 9. Sand boiling

Figure 10. Liquefaction in slopes

Figure 11. Lateral flow induced damage

Figure 12 shows a slope collapse possibly caused by liquefaction that occurred between the river's embankment and the sand extraction center located on the bank of Sabaishi river (Yamamoto, Kashiwazaki City). As observed from Figure 13, the slope collapse resulted in the subsidence of the road, and the displacement of the embankment inwards. In the mid-section of the collapsed slope sand boilings could be seen, and therefore it could be deduced that the lower section recorded a sudden drop in strength due to liquefaction, thus leading to a large-scale collapse coupled with lateral displacement. Due to liquefaction and accompanying lateral flow of the ground (Figure 14), a neighboring house suffered displacement, thus affecting its basement and supporting walls.

Figure 12. Liquefaction

Figure 13. Lateral flow and subsidence

Figure 14. Lateral flow

Due to liquefaction, differential settlement and uplifting of underground pipes and structures occurred in areas (Hashiba district, Kashiwazaki City) along the former river channel region of the Sabaishi River (Figure 15). The differential settlement affected the foundations of the houses, although damages were small (Figure 16).

4.3 Liquefaction of natural ground

Liquefaction was also observed in the natural ground of Sabaishi River Commemorative Park (Kashiwazaki City). Within the island in between the new and former river channels of the Sabaishi River, liquefaction occurred, resulting in ground subsidence wherein a continuous fissure measuring 100 m long was found running parallel to the river (Figure 17). At the end of the fissure, several instances sand boilings indicative of liquefaction could be observed. The U-shaped drain located in the center of the island shown in Figure 18 is indicative of ground subsidence due to which the drains were subjected to pressure, and thus lifting them upwards. The failure mechanism of this type of ground subsidence remains unclear and need further studies (such as testing of the soils) in the future.

Figure 15. Differential settlement

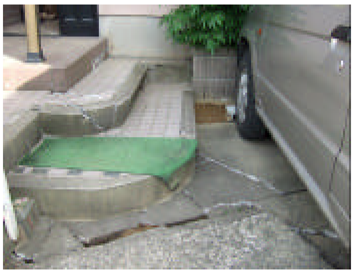

Figure 16. Damage to house

Figure 17. Ground subsidence

Figure 18. Uplifting due to lateral flow

4.4 Damages to RC buildings and important facilities

In the main building of Niigata Prefectural Aqua Park (Kashiwazaki City), large-scale subsidence caused by liquefaction of soils occurred. Figure 19 shows the state near the entrance area, where severe damage was inflicted on the foundation as a result of the ground subsidence with a maximum depth of 1m. Figure 20 shows the damages inflicted on the underground infrastructure in the surrounding areas, such as manholes and sewerage pipes. There were instances of manhole uplifted by about 70 cm above the ground. Even on the edge of a road little away from the Aqua Park building, sand boilings were observed, wherein the paved road settled, along with uplifting of the sewerage pipes.

Figure 19. Entrance of the building

Figure 20. Uplifting of underground structures

Figure 5. Cracks around incinator building in TEPCO power plant

Kashiwazaki-Kariwa nuclear power plant belonging to Tokyo Electric Power Corporation (TEPCO) had suffered damages during the earthquake. A comprehensive report of the hazards caused to the nuclear power plant facilities can be found in Sakai et al (2009). Ground subsidence of a few tens of cm to 1 m occurred widely on the premises of the Kashiwazaki-Kariwa Nuclear power Station. In particular, large subsidence of 1 m or more occurred around the reactor and turbine buildings, and damage to nearby equipment was caused by differential settlement between buildings and equipment. According to Sakai et al (2009), subsidence occurred mainly in unsaturated soil around buildings under the influence of sub-drainage. Sand boils caused by liquefaction were observed at many locations in the ocean side areas, where subsidence and cracking were also observed. Example of this type of cracks in the Arahama side area is shown in Figure 20. These cracks occur around the buildings because of the differential settlement between buildings and the surrounding ground.

5. CONCLUSIONS

The major cause of the damages to structures by the 2007 Niigataken Chuetsu-oki Earthquake could be attributed either to strong ground vibration or to ground deformation due to liquefaction. This preliminary investigation has revealed that the cause of several wooden houses (non-engineered) that were totally destroyed or damaged, were largely due to the lack of resilient walls, incomplete joints, heavy tiled roof, the unbalanced placement of resilient walls, and decayed structural parts. These buildings did not possess full earthquake-resistant capabilities. Although partial damage could be observed in buildings which sufficiently complied with the Building Standard Law, it could be seen that there was no evidence of total destruction or significant deformation in such buildings. Buildings that did incur slight damage might possibly have deficiencies in their planning, faulty construction, and inappropriateness of the foundations to counter liquefaction related damages. Specific considerations, thus, need to be placed on these buildings, in order not to repeat the similar devastation in the future earthquakes.

Damages in the newly built buildings, which either tilted or developed cracked, were due to soil liquefaction and lateral displacement of the embankments nearby. Buildings founded on weak subsoils suffered both vertical and horizontal displacements due to soil liquefaction resulting in heavy damages to these buildings. On the other hand, subsidence of unsaturated soils as well as the saturated soils could be attributed to the damage suffered by the Kashiwazaki-Kariwa nuclear power plant facilities of TEPCO.

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