Preliminary Reconnaissance Report on the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake

Excerpts (index and summary)

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This report contains excerpts (an index and summary of major points) from the *Preliminary Reconnaissance Report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake* (Architectural Institute of Japan, July 2011).

Research Comittee on Disaster, Architectural Institute of Japan

Index: Preliminary Reconnaissance Report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake (Architectural Institute of Japan, July 2011).

Summary

We have prepared a preliminary reconnaissance report pertaining to three recent earthquakes—a magnitude 9.0 earthquake that occurred off Miyagi Prefecture on 11 March 2011 (the Great East Japan Earthquake), a magnitude 6.7 earthquake that occurred in northern Nagano Prefecture on 12 March 2011, and a magnitude 6.4 earthquake that occurred in eastern Shizuoka Prefecture on 15 March 2011. Presented herein is a summary of this report.

1. Outline of earthquakes

1) On 11 March 2011, one of the strongest earthquakes to strike Japan in recorded history occurred at a depth of 24 km off the coast of Miyagi Prefecture. This subduction-zone earthquake, which had a magnitude of 9.0, resulted from thrust faulting on the boundary between the Pacific plate and the North America plate (on which rests eastern Japan). This event is officially called the Tohoku-Chiho Taiheiyo-Oki Earthquake.

2) Direct factors triggering this earthquake are presumably a magnitude 7.3 earthquake that occurred west of the 11 March earthquake's epicenter (i.e., also off the coast of Miyagi Prefecture) on 16 August 2005 and a magnitude 7.3 earthquake that occurred just two days beforehand (9 March 2011) off the Sanriku coast. The 11 March earthquake produced a substantial 25–30 meter slip along the west side of the Japan Trench axis all the way from the sea off the Sanriku coast in the north down to the sea off Ibaraki Prefecture in the south.

3) One feature of the 11 March earthquake was that its seismic waves came in at least two clusters with the second cluster even stronger than the first. The maximum acceleration of the second cluster was recorded at approximately 100 s after the starting time of motion. Only one of the two major clusters was widely felt in the Kanto region.

4) The maximum reading on the Japan Meteorological Agency's seismic intensity scale, a reading of 7, was recorded at only one location—the city of Kurihara, in Miyagi Prefecture—while 6-upper readings were recorded at 40 locations in four prefectures. Strong motion records having peak acceleration in excess of 1,000 Gal were recorded at 18 locations, although all had principal frequencies of 5 Hz or above. Pseudo-velocity response spectra also showed principal frequencies of around 1 Hz and 5 Hz, and peak velocity exceeded 100 cm/s at only one measurement location, in Kurihara. A comparison with a strong motion record for the Great Hanshin (Kobe) Earthquake reveals that although the 11 March earthquake lasted for a very long time, relatively speaking, its ground motion did not have a dominant period in the intermediate range of around 1 s, which

could lead to particularly heavy damage.

5) The 11 March earthquake presumably had some influence on two events that followed, specifically a magnitude 6.7 earthquake that occurred in northern Nagano Prefecture on 12 March and a magnitude 6.4 earthquake that occurred in eastern Shizuoka Prefecture on 15 March. Although readings of 6-upper on the JMA seismic intensity scale were recorded locally in both prefectures, the seismic intensity of these earthquakes was generally low in surrounding areas, and the principal frequencies of their shocks were approximately 5 Hz.

2. Topography and geology

1) This series of earthquakes caused extensive damage over much of eastern Japan. Damage was particularly heavy in Iwate, Miyagi, and Fukushima prefectures, all in the Tohoku region; Ibaraki and Chiba prefectures, both in the Kanto region; Sakae-mura, in Nagano Prefecture; and Fujinomiya, in Shizuoka Prefecture. The geological and geomorphological characteristics of these areas are diverse; included are basins, hills, alluvial plains, coastal areas, and even landfill.

2) Trending north-south along the western edge of the three Tohoku prefectures (Iwate, Miyagi, and Fukushima) is the Ou Range, composed primarily of Cretaceous granitic and Neogene rock. In Iwate, that range, together with the Kitakami Mountains, which trend north-south along the eastern edge of the prefecture, forms a basin where cities such as Morioka, Hanamaki, and Kitakami are located. In Miyagi, an alluvial plain (the Sendai Plain) extends throughout the center of the prefecture. On it are located Sendai, Natori, Ishimaki, and numerous other cities. In Fukushima, the Ou Range, together with the Abukuma Mountains running roughly parallel to the east, forms the Naka-dori, or central valley, within which the cities of Fukushima, Koriyama, and Sukagawa, among others, are located. The coastline runs to the east of the Abukuma Mountains, forming between the two the Hama-dori, or coastal region, on which sit the cities of Soma and Iwaki.

3) The northern part of Ibaraki Prefecture contains several mountainous regions, most notably the Abukuma and Yamizo mountains, while the southern part, comprising the Hitachi Upland and the downstream basin of the Tonegawa River, is notable for a considerable degree of urban development, including the cities of Mito and Tsukuba. The Hitachi Upland itself consists of numerous plateaus, the terraces of which tend to be covered with a thick layer of Kanto loam over relatively soft sand and gravel strata. Chiba Prefecture likewise can be generally classified into a northern part, specifically the Shimousa Upland and its peripheral lowlands, and a southern part where hills predominate. The Shimousa Upland itself comprises the Narita Group

(marine strata formed during the Pleistocene epoch) and, on top of that, layers of Kanto loam. Numerous cities are located on the upland, including Noda, Funabashi, and Narita. The northwest section of the Chiba Prefecture runs along the north side of Tokyo Bay, where the ground is naturally low and, in many cases, presently covered by landfill. Indeed, more than 70% of the city of Urayasu is built on landfill.

4) Sakae-mura, a village, is located on the Chikuma River basin within the interior of northern Nagano Prefecture. Fujinomiya, a city, is located to the west of Mount Fuji in the interior of eastern Shizuoka Prefecture. The center of the city lies within the Fujinomiya Lowlands, a fault angle basin.

3. Outline of tsunamis

1) Based on readings from GPS wave buoys placed in waters 100–300 m deep roughly 10–20 km off the Pacific coast, the first tsunami surge was recorded from the area off northern Iwate Prefecture (Kuji) down to the area off Fukushima Prefecture (Onahama) at 14:50, immediately after the occurrence of the earthquake (14:46). The largest surge was recorded from 15:12 to 15:19, approximately 30 min after event. The tsunami height was 2.6–6.7 m, with the maximum value recorded off southern Iwate Prefecture (Kamaishi).

2) Waveforms recorded off southern Iwate (Kamaishi) reveal that the first surge was particularly high, with the height gradually decreasing in subsequent surges. Even the seventh surge, which occurred 6 h after the first, was still higher than the largest tsunami generated by the 2010 Chile earthquake.

3) The tsunami height was generally 8–9 m off the coast from Miyako (Iwate Prefecture) down to Soma (Fukushima Prefecture). The inundation height tended to progressively increase from Misawa toward the south, exceeding 10 m around Kuji and reaching roughly 10–15 m along the Sanriku coast from northern Iwate Prefecture to Oshika Peninsula (Miyagi Prefecture). Inundation was relatively low along Matsushima Bay at 5 m or less but nonetheless exceeded 10 m along the coast from Sendai Bay down to Soma. Extremely high tsunami run-up heights were recorded within those regions, most notably 40.5 m at Miyako.

4) As for the Kanto region, the first surge (height: 1.8 m) arrived at Oarai (Ibaraki Prefecture) at 15:15, with maximum tsunami height (4.2 m) recorded at 16:52. At Choshi (Chiba Prefecture), the first surge (0.4 m) arrived at 15:13, with maximum height (2.4 m) recorded at 17:22. Note that the largest surge reached Ibaraki and Chiba prefectures approximately 2–2.5 h after the earthquake. Tsunami height, at approximately 3–5 m off Ibaraki, 3–4 m off northern Chiba (Kujukuri), and 3 m off southern Chiba (outer (Pacific) coast of the

Boso Peninsula), tended to decrease from Ibaraki down south to Chiba. However, high tsunamis were recorded locally within those two prefectures, including 7.2 m off Hirakata, Kita Ibaraki (Ibaraki Prefecture) and 7.6 m off Iioka, Asahi (Chiba Prefecture).

5) The tsunami surges produced by the main earthquake were the largest ever recorded in Japan. This event caused widespread destruction along not only the Sanriku coast, which has been frequently struck by earthquake-induced tsunamis in the past and also has a complicated geomorphology (including a sawtooth (ria) coastline) that tends to amplify the effects of a tsunami, but also along the coast, which heretofore has largely escaped extensive damage, from Sendai Bay down to Fukushima, northern Ibaraki Prefecture, and Kujukuri and the outer Boso Peninsula of Chiba Prefecture.

4. Damage statistics

1) There are 22,801 people listed as dead or missing as of 30 June 2011. The toll is highest in Miyagi Prefecture at 13,803 people, followed by Iwate at 6,942, Fukushima at 1,754, Ibaraki at 25, and Chiba at 22. Fatalities were also reported in the prefectures of Hokkaido, Aomori, Yamagata, Tochigi, Saitama, Tokyo, and Kanagawa. There were seven fatalities in Tokyo but less than five in each of the others. Nationwide, a total of 5,565 people are listed as injured.

2) The proportion of dead/missing relative to population for specific communities runs highest for Otsu-cho at 11.3% and Onagawa-cho at 10.3%, among communities in Iwate and Miyagi prefectures, respectively. The tsunami event presumably accounted for the large majority of fatalities. According to a survey conducted on 9 April by the Metropolitan Police Office and later reported by *Asahi Shimbun*, elderly people—those 65 years of age or older—accounted for the majority of fatalities at 55.4%, followed by those in the 40–64 age bracket at 27.9%, the 19–39 age bracket at 10.0%, the 7–18 age bracket at 3.9%, and the 0–6 age bracket at 2.8%.

3) As of 30 June, the number of buildings listed as totally destroyed is 105,940. Miyagi Prefecture accounts for the majority, at 65,492 buildings, followed by Iwate at 20,998, Fukushima at 15,897, Ibaraki at 2,163, Chiba at 771, Aomori at 306, and all other prefectures at a total of less than 100. Nationwide, 107,855 buildings are listed as partially destroyed and 426,405 buildings are listed as damaged.

4) A total of 95,227 buildings were examined within a series of emergency risk assessments conducted by various prefectural governments soon after the Great East Japan Earthquake, wherein 11,557 were assessed as unsafe and 23,149 as requiring caution. Miyagi Prefecture had the most buildings judged unsafe, at 5,088, followed by Fukushima at

3,314, Ibaraki at 1,561, Chiba at 677, Tochigi at 676, Tokyo at 59, Gunma at 30, and Kanagawa at 4. Similarly, a total of 2,318 buildings were examined after the 12 March earthquake in northern Nagano Prefecture, of which 297 buildings were judged unsafe in Nagano and 78 in Niigata. In addition, a total of 513 buildings were examined after the 15 March earthquake in eastern Shizuoka Prefecture on 15 March, whereupon 13 buildings in that prefecture were judged unsafe.

5) With lifeline systems cut by the earthquake and dwellings swept away by tsunamis, many people immediately fled to evacuation centers. There were approximately 470,000 evacuees nationwide as of 14 March, of which roughly 410,000 had gone to approximately 2,000 evacuation centers located within the three Tohoku prefectures of Iwate, Miyagi, and Fukushima. The number of evacuees gradually diminished as lifeline systems were restored and temporary housing was built. Nonetheless, there remained as of 11 May, exactly 2 months after the earthquake, a total of 115,000 evacuees (evacuation center occupants) nationwide, of which 94,000 were within the three aforementioned Tohoku prefectures.

6) As of 25 June, total damages were approximately ¥16.9 trillion, of which buildings and other structures account for roughly ¥10.4 trillion, lifeline systems for ¥1.3 trillion, societal infrastructure for ¥2.2 trillion, agricultural and fisheries related facilities for ¥1.9 trillion, and "other" for ¥1.1 trillion. Damage was especially heavy in the Tohoku region, breaking down by prefecture as roughly ¥6.4 trillion in Miyagi, ¥4.3 trillion in Iwate, and ¥3.1 trillion in Fukushima (all three figures as of 13 May). Note that these figures respectively correspond to 11.9% of the total asset base of Miyagi Prefecture and 12.6% of that of Iwate Prefecture.

5. Damage to wood buildings

1) Substantial vibrational damage to buildings and structures, including collapse or other heavy damage to houses, occurred over a wide swath from Tohoku down to northern Kanto, although in only a fairly limited number of clusters.

2) Collapse and other heavy damage affecting wooden houses, which tend to have long natural period and little seismic protection, were extensive in areas having weak ground (along river beds, etc.). Also reported was damage to earthen wall storehouses or other buildings not only in areas where houses in general suffered severe damage, but also in areas where they suffered little damage.

3) Slight damage, typically to roof tiles (especially fallen ridge tiles) and exterior wall coverings (peeling, etc.) was observed over a wide area extending from Tohoku to Kanto.

4) Particularly conspicuous in the aftermath

of this earthquake are (1) collapse or other severe damage to houses and other structures as a result of landslides or failure of retaining wall on slopes, especially on land developed for residential use, and (2) tilting or sinking of entire structures as a result of the liquefaction of sandy soils. Furthermore, many of the areas that experienced significant vibrational stress are characterized by weak soil, and in several cases it is not entirely clear whether damage to structures there should be attributed to vibration or to ground deformation.

5) As for tsunami damage, many wood buildings were swept away within areas struck particularly hard. There were cases, however, of wood buildings that, because they were shielded from direct tsunami impacts by relatively large surviving structures, remained in place. There were also cases where low-rise wooden dwellings presumably having excellent structural specifications remained in place despite the lack of a shielding building, although some did suffer severe damage to their walls or frames. The use of hold-down bolts appeared not to be an important factor in determining whether a wood building was swept away.

6. Damage to reinforced concrete buildings

1) Although not great in number, some reinforced concrete buildings in need of rebuilding/repair because of collapse or other severe damage were observed. More numerous were buildings that despite suffering only moderate or slight damage were nonetheless unfit for further utilization. Many of the damaged buildings predate 1981 (current seismic standards were implemented in June 1981), and a good number of the buildings that suffered particularly severe damage were built before 1971 and had not been seismically reinforced afterwards(shear design codes for reinforced concrete buildings were implemented in June 1971). The large majority of buildings built after the current earthquake standards took effect (along with buildings built before the standards took effect but subsequently reinforced) suffered only slight damage. Several cases were observed in which buildings that were undergoing retrofitting, but not fully reinforced, suffered considerable damage to their unreinforced portions.

2) Also observed were (a) cases of damage apparently attributable to amplification of ground motion by geological or geomorphological effects, and (b) cases of foundation tilting or sinking apparently attributable to pile damage or soil collapse.

3) With regards to member damage, shear fracture and axial collapse of long and short columns were observed. Such damage was apparently due to the following factors: an insufficiency of shear reinforcement bars, a concentration of seismic forces, high

torsional forces within long spans, or the use of piloti columns. Also noted were damage to and collapse of concrete junction areas within buildings having a hybrid structure of reinforced concrete in some parts and steel or wood in others.

4) Many buildings were rendered unusable, despite a lack of serious damage to structural members, by damage to nonstructural elements (mullion walls, etc.) or cave-ins of ceiling material. This phenomenon was also apparent in relatively new buildings built after the new seismic-strength standards took effect. As for tsunami-induced damage, little damage was observed to structural members in school buildings but considerable damage to nonstructural members and finishings. Many such buildings could be difficult to repair.

5) Steel-reinforced concrete buildings typically remained close to their original condition even in areas where the large majority of wooden structures had been swept away by the tsunami. However, in Onagawa and certain other areas some smaller buildings had tipped over upon being completely submerged. Also observed were buildings that, while remaining in place, nonetheless suffered wall damage caused by perpendicular strikes by wave surges or drifting objects.

7. Damage to steel-reinforced concrete buildings

1) Almost all damage to steel-reinforced concrete buildings was to nonstructural members, whereas little damage to structural members was observed. However, some buildings designed under the old seismic design codes suffered severe structural damage. Story collapse in the middle floors of steel-reinforced concrete buildings, which was one of the characteristics of the 1995 Great Hanshin Earthquake was not observed in structures damaged by the 2011 earthquakes discussed here.

2) Notable types of structural damage apparent in steel-reinforced concrete buildings within the city of Sendai include flexural cracking or shear cracking of columns, shear failure of column bases, flexural cracking or shear cracking of beams, flexural yielding of beams (crushing of concrete at the ends of beams), shear failure or bond-splitting failure of coupling beams (including beams with openings), cracking of reinforced concrete braces, shear cracking of shear walls or concrete crushing at its base, flexural failure of multi-story shear walls, severe damage to portions of elevator shafts, damage to pile foundations, and damage to rooftop structures.

3) As for nonstructural members, the following damage was observed: shear cracking and shear failure of nonstructural walls (spandrel walls, wing walls, and stud

walls), horizontal cracking of concrete construction joints at stairwells, jammed (unopenable or unclosable) doors, tile peeling, expansion joint damage, damage or collapse of ceiling panels, damage or collapse of autoclaved lightweight concrete (ALC) panels, damage to connecting corridor concrete, damage to glass blocks, damage to hand railings, and damage to building peripheries due to ground subsidence.

8. Damage to reinforced concrete boxed wall-buildings and masonry structures

1) A total of 634 public apartment buildings having three structural types were examined within the city of Sendai.

Of the 496 buildings having a reinforced concrete boxed wall (WRC) structure, 97.4% were found to be undamaged or to have only slight damage. Among the remaining 2.6%, only one building had moderate damage and no buildings had severe damage (the others had minor damage).

All of the 47 buildings having a precast prestressed reinforced concrete boxed wall (WPCaPS) structure in Sendai were found to have suffered no or slight damage. However, there was one WPCaPS building in Natori which suffered severe damage to its foundation structure.

Of the 91 buildings having a boxed wall of thin ribbed panel structure, 72.5% were found to have suffered no or slight damage. Among the remaining 27.5%, 11 buildings were moderately damaged and 1 building was severely damaged.

Common to all three structural types is that structural damage was apparently promoted by ground deformation in the vicinity of the building.

2) In the above investigation in Sendai, only one of the WRC buildings examined was within an area exposed to a seismic intensity of 7, and it suffered slight damage. In areas where coexisting WRC, WPCaPS, and ribbed panel buildings were together exposed to a seismic intensity of 6-upper, WRC and WPCaPS buildings suffered approximately the same degree of damage, whereas ribbed panel buildings suffered relatively higher damage. This is probably because 71 out of the 91 ribbed panel buildings were constructed before the new earthquake-resistance standards took effect in 1981.

3) WRC and WPCaPS buildings within coastal areas in Miyagi Prefecture, where tsunami damage was particularly severe, did not encounter any major structural damage, although they did suffer some damage to balconies and the like. In addition, there were ribbed panel buildings in which the panels themselves were damaged.

4) Along the Miyagi coast, some reinforced

hollow concrete block masonry buildings were observed that had fallen over or collapsed as a result of the tsunami, or tilted as a result of soil washing out from under the foundation. Partial collapse of nonbearing concrete block masonry walls was also observed.

In an investigation of areas in Sendai somewhat removed from the coastline, no notable damage was observed to the following: reinforced hollow concrete block masonry buildings, reinforced fully grouted concrete masonry buildings, or nonbearing concrete block masonry walls.

5) Masonry structures in northern Miyagi Prefecture and part of Iwate Prefecture were also investigated. With regards to stone buildings, large cracks in stone walls, outward collapse of gables, tsunami-induced collapse, and other damage were observed. On the other hand, some seismically retrofitted stone buildings were found to be entirely undamaged.

6) An investigation of concrete block garden walls in Miyagi Prefecture revealed the following: collapse due to ground deformation, collapse of unreinforced portions due to illegal construction; tip-over and collapse due to insufficient anchoring of vertical bars into foundations or due to insufficient embedding of the foundation into the ground, tilting or collapse due to rebar corrosion, major cracking at joints along the horizontal top rebar, and tsunami-induced tip-over and collapse. An investigation of the Natori district showed that 16% of the concrete block garden walls examined had tipped. Severe damage to non-reinforced stone garden walls was observed.

9. Damage to steel buildings

1) Buildings presumably built after the current seismic design code took effect suffered little structural damage due to ground motion, although some damage was observed in nonstructural elements (interior and exterior finishings, ceilings, etc.). Structural damage was apparent in buildings presumably built before the current code came into effect. Damage induced by ground motion to such buildings included damage to beam-to-column connections, buckling/joint deformation/fracture of diagonal bracing, cracking of column base concrete, and plastic elongation/fracture of anchor bolts. This pattern of damage is similar to what has been reported from earlier earthquakes.

2) Among damage to nonstructural members are many reported cases of ceiling or exterior finishing damage or collapse within steel buildings having relatively long spans (gymnasiums, factories, etc.). This is particularly the case for dry-construction (prefabricated) ceiling frames that utilize light-gauge steel supports.

3) With regards to tsunami damage, some buildings whose column bases fractured were washed away with hardly a trace. Some buildings, while free of column base fracture, tilted or collapsed because of failed joints or members. Some buildings had their exterior finishings washed away, even though their structural skeletons remained in place. The type and extent of damage varied considerably depending on tsunami inundation height and other factors. Apparent in areas struck by extremely large tsunami waves were buildings that saw little damage to their primary structural members because their exterior/interior finishings were washed away. Yet, even in such cases, structural members were often damaged by the impact of debris carried by the tsunami. In areas less severely struck by the tsunami, steel buildings saw varying degrees of nonstructural damage, depending on the tsunami height. However, the majority of buildings saw limited structural damage.

10. Damage to nonstructural elements

1) As for wooden housing and similar structures, damage to roof tiles was observed over a wide geographical area, and damage to ridge tiles was almost always accompanied by damage to clay tile roofing. Damage to wet-applied outer walls was also observed in cases.

2) The following damage was also noted: collapse of ceiling panels in large halls; collapse of ceiling panels, lighting fixtures, insulation, and other such materials in gymnasiums; and damage to tie-in points between ductwork and ceiling panels within cafeteria kitchens. Such ceiling panel damage occurred even within buildings erected after technical guidance on that issue was issued and was even apparent in a relatively new airport terminal building, in which a portion of the ceiling collapsed. Many ceiling collapse and the like were also observed in general buildings. Particularly common was the collapse of ceiling panels from ceiling frames consisting of lightweight steel supports (joists). Similarly, within relatively large, steel-framed commercial facilities having upper parking floors, wide-scale ceiling collapse was often observed in lower storefront floors. This type of damage was evident even in relatively distant locales such as Chiba Prefecture and, as with other types of nonstructural damage, tended to increase in severity with increasing proximity to the epicenter (a tendency apparent within Tochigi, Ibaraki, and the Tohoku prefectures). The primary forms of damage were slippage of ceiling panels from lightweight steel support frames, collapse of the ceiling panels themselves, and deformation/collapse of the support frames themselves.

3) Widely observed was damage to external tile walls of reinforced concrete buildings; lath sheets of steel buildings; ALC panels, glass screens, and window glass of steel buildings; and external walls, external

finishings, and openings of other types of buildings. Other damage includes that to interior glass, hanging smoke barriers, extended eave walls, expansion joints, and miscellaneous works.

11. Damage to soils and foundations

1) Ground subsidence, presumably due to diastrophism (deformation of the Earth's crust, especially folding and faulting), was measured at 76 cm at Ofunato (Iwate Prefecture) and 56 cm at Kesennuma (Miyagi). Subsidence was also quite notable around the present mouth of the Kitakami River in Ishimaki (and also around the river’s historical mouth). Parts of the central business and residential districts of that city are now at sea level (SL +0 m).

2) Extensive liquefaction was observed along the coast of Tokyo Bay and around the Tonegawa River floodplain. Liquefaction primarily occurred within relatively new landfill, with numerous sand boils and large (approximately 50 cm) ground subsidence, leading to settlement/tilting of wooden and reinforced concrete buildings supported on spread foundations, uplift of underground structures (pipelines, etc.), and collapse of roadways. Nonetheless, no structural damage was observed to the superstructures of pile-supported buildings. In addition, no cases of structural damage were apparent in the superstructures of buildings built on spread foundations (including mat foundations) having a high degree of rigidity, despite their settlement and/or tilting.

3) Within emergency risk assessments, a total of 886 houses were judged to be dangerous in Miyagi Prefecture, 269 in Fukushima Prefecture, and 98 in Iwate Prefecture. Of those 886 in Miyagi Prefecture, the large majority—794 houses—were in the city of Sendai. Many of the damaged houses within residential areas were damaged not by simple collapse of retaining walls, but rather by slope failure.

4) Several cases of settlement and tilting of pile-supported buildings were observed in the city of Sendai, implying damage to the pile foundations themselves. Ground subsidence (approximately 10 cm), sometimes the apparent result of sand boils and liquefaction, was evident around these buildings.

5) Within Onagawa and Rikuzen-Takata, several steel and reinforced concrete structures were noted that, having suffered damage to their pile foundations, were knocked over by tsunami surges. Much of the pile damage was to the (a) joint between the pile cap and the pile and (b) the area around the pile head. The buildings suffering such damage were old; apparently their pile foundations were not designed to withstand earthquakes. We infer that the pile cap joints or the piles themselves were fragile and, as a result, damaged by the earthquake to some extent, making them

unable to withstand tsunami wave pressure and buoyancy forces.

12. Damage to historical structures

1) There were 578 reported incidents of damage to designated cultural properties as of 7 June 2011 (note that two or more buildings within the same site are counted as one property). These include 115 properties in Ibaraki Prefecture, 82 in Miyagi, 78 in Tochigi, 61 in Gunma, 45 in Fukushima, 45 in Tokyo, and 31 in Iwate. Damage was also reported within six important preservation districts for groups of traditional buildings.

2) Not least because there are so many historical structures, a good number of registered tangible cultural properties—290 structures, to be exact—were reported to be damaged. This corresponds to approximately 15% of all such structures within a broad swath running from Tokyo north through 11 prefectures up to and including Aomori.

3) No less than 130 structures listed as national treasures or important cultural properties and located within Tokyo or 14 prefectures were reported to have suffered some of the heaviest damage they had ever encountered under natural circumstances. However, few such structures were heavily damaged by ground movement. Furthermore, the only damage caused by tsunamis was an inundated floor within one designated important cultural property.

4) The destructive forces of the March 2011 earthquake do not extend that far beyond what has been encountered in the historical past. The following damage to historical wood structures was observed: (1) misalignment with (slippage on) foundations; (2) cracking, peeling, and caving of earthen walls (particularly within earthen wall storehouses); pertaining to the framework between the foundation and roof, (3) partial leaning, separation between attached *geya* penthouses and main dwellings; and pertaining to roofs, (4) misalignment and falling of pantile roof tiles. Among damage to masonry structures were cases of serious structural cracking within their frames.

5) Generally speaking, little damage was apparent to structures that had undergone repair in recent years, particularly those which had also been structurally reinforced. On the other hand, the earthquakes acted to abruptly accelerate damage in structures which had sagged or tilted through the years and were due for repair. In some cases, seismic forces acted to tilt the framework between the foundation and roof to such an extent that the structure now appears on the verge of collapse.