

The Great East Japan Earthquake Damage Report

The Building Research Institute of Japan has conducted an extensive survey of the damage caused to buildings and homes by seismic motion and tsunami waves during the 2011 Great East Japan Earthquake, and offers this report. (Detailed data including damage due to tsunami: <http://www.kenken.go.jp/english/index.html>)



The tsunami swept away all the wooden and low-rise buildings in this coastal area of Onagawa, Miyagi Prefecture, except for a solitary reinforced concrete building.

At 2:46 p.m. on March 11, 2011, what is formally known as the “2011 off the Pacific coast of Tohoku Earthquake” struck, with an epicenter off the coast of Sanriku. Casualties from the disaster stand at 15,839 fatalities and 3,642 missing. Damage to buildings includes 120,241 buildings completely destroyed, 189,822 buildings partially destroyed and 598,587 buildings partially damaged (announced by the National Police Agency as of November 17, 2011).

While the size of the earthquake was reported as magnitude 7.9 by the Japan Meteorological Agency immediately after it struck, on March 13 this was revised to 9.0 (on the moment magnitude scale). An earthquake of this size was Japan’s largest in recorded history, and the scale of damage it caused was also greater than ever experienced.

The tsunami waves that arrived along the coast shortly after the earthquake hit reached far inland over a vast area from Aomori Prefecture in the north to Chiba Prefecture in the south, resulting in immense damage.

To obtain technical data to be used in a review of technical standards in light of the earthquake, after the earthquake struck the Building Research Institute (BRI) and the National Institute for Land and Infrastructure Management (NILIM) set about the task of collecting information on damages due to seismic movement and the tsunami waves, focusing primarily on building structures.

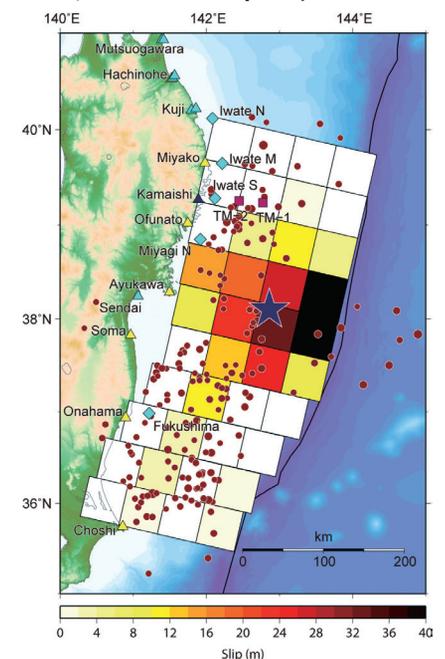
The shaking experienced around the country is important information through which we can understand the structural damage caused by the earthquake. To look at this, we will introduce strong motion seismograms recorded in the disaster-affected regions, which were obtained through the strong-motion earthquake observation project conducted by the BRI. The epicentral area of this earthquake was extremely large, and regions experiencing strong motion occurred across the widest area ever seen.

While buildings also suffered damage, buildings constructed according to the new earthquake resistance standards did not suffer major damage. In light of lessons learned from earthquake damage due to the 1978 Miyagi earthquake and others, Japan strengthened its seismic design standards in accordance with the Building Standards Law and related ordinances from June 1981. These standards are known as the new earthquake resistance standards.

Large Epicentral Area

The earthquake was felt across a wide

Figure 1: Distribution of slip amount on the fault estimated from tsunami measurements (Fuji et al., 2011, Earth, Planets and Space)



area from Hokkaido to western Japan. As the earthquake occurred along what is known as a plate boundary, the ruptured epicentral area was large, and the resultant aftershock area is estimated to have been around 500 km to the north and south, and around 200 km to the east and west. The seismic rupture began around the area indicated by the ★ symbol in Figure 1, and according to BRI analysis, the largest slip amount of about 48 meters occurred in the vicinity of the ocean trench where the plate boundary is located. It is also estimated that between 10 and 30 meters of slip amount occurred from off the coast of Miyagi Prefecture to the southern Sanriku Coast, approximately ten meters off the Fukushima coast and roughly two meters off the coast of Ibaraki Prefecture. Off the central Sanriku coast, slip amount of between five and eleven

Figure 2: Distribution of seismic intensity for each region during the main shock

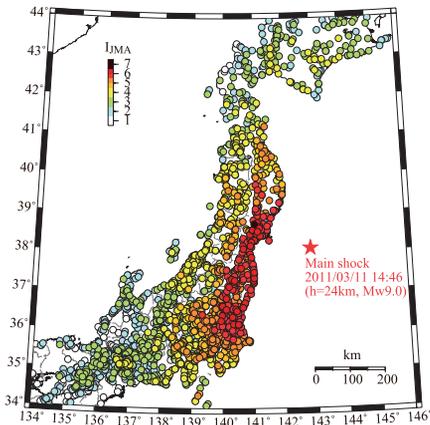


Figure 3: Records obtained from BRI strong motion observation stations

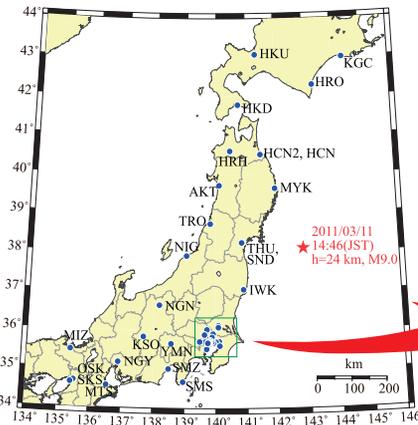
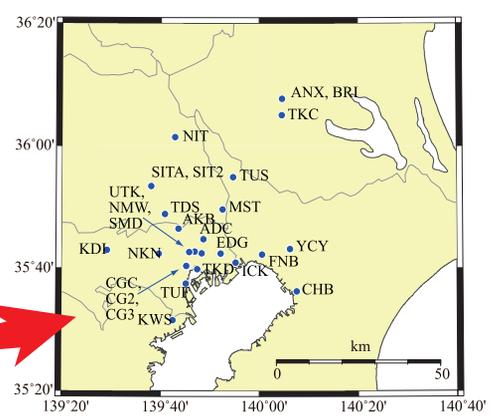


Figure 4: BRI strong motion observation stations in the Tokyo metropolitan area



meters is estimated in some areas. The ★ symbol in Figure 1 indicates the starting point of the rupture which represents the beginning of the earthquake. From this point the rupture widened as far as off the coast of Iwate Prefecture to the north and Ibaraki Prefecture to the south, resulting in a vast epicentral area.

Widespread Shaking

In Japan, the size of earthquake shocks is expressed in terms of the Japan Meteorological Agency (JMA) Seismic Intensity Scale. The largest seismic intensity recorded during the 2011 earthquake was level 7 at the Tsukidate station in Kurihara, Miyagi Prefecture. No other areas recorded level 7 intensity. However, in terms of peak ground acceleration, which is an alternate indicator of shaking used by strong motion observation networks operated by other agencies such as K-NET^{*1}, this measurement surpassed 1,000 Gal^{*2} at many observation stations. As Figure 2 shows, the shocks

were felt across almost all of Japan.

*1 K-NET: A ground-based strong-motion earthquake observation network installed across Japan by the National Research Institute for Earth Science and Disaster Prevention and the system which transmits strong-motion recording data via the Internet.

*2 Gal: Unit of acceleration (1 gal = 1 cm/s²)

The seismic intensity readings shown in Figure 2 are calculated from ground-based observation records. Seismic movements vary not only according to the size of an earthquake and the distance from the epicenter, but also due to ground conditions at the observation point.

To determine whether a building is resistant to earthquakes, it is important to determine not only the response of the building during an earthquake, but the seismic motions which acted upon

the building at the time. This is easy if seismic observations are conducted in buildings. The BRI conducts seismic observations targeting buildings at approximately seventy locations nationwide with the aim of measuring the earthquake resistance of buildings.

Figure 6: Characteristics of seismic movements in disaster-affected regions (inside buildings). The stated level is exceeded at 2 and 3 seconds into the cycle, but this is not a problematic level.

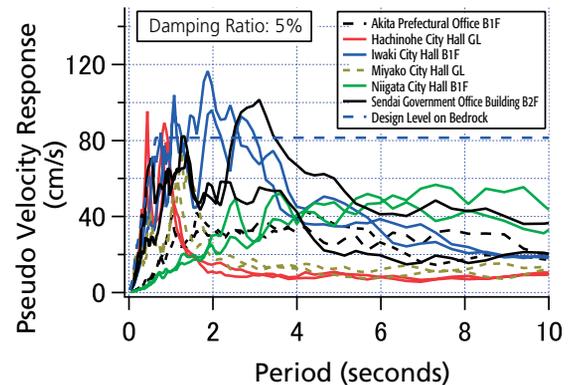


Figure 7: Seismic motion characteristics at observation stations in the Tokyo metropolitan area (first floors, basement floors or ground surface)

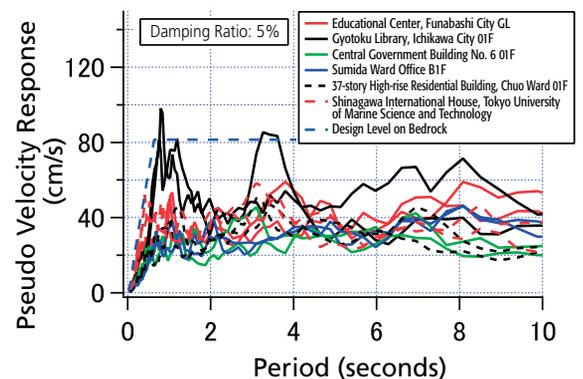


Figure 5: Comparison of observed waveforms (velocity waveforms) for the same building during the 1978 Earthquake off the Coast of Miyagi Prefecture (blue) and the 2011 Earthquake off the Pacific coast of Tohoku (black)

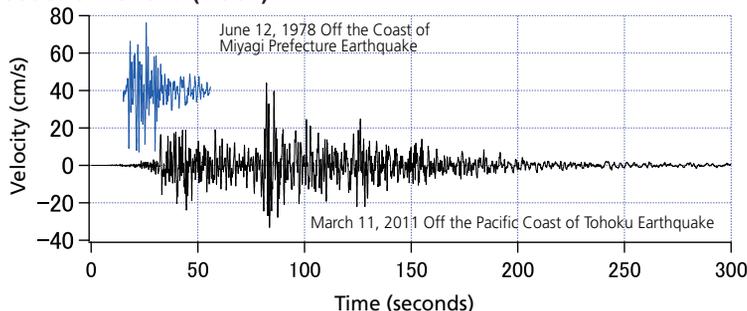


Table 1: Main strong motion records obtained by BRI

Code	Station Name	_ (km)	I _{MA}	Loc.	Max. Acc. (cm/s ²)		
					H1	H2	V
SND	Sendai Government Office Bldg. No. 2 (high-rise)	175	5.2	B2F*	163	259	147
				15F	361	346	543
THU	Tohoku University Civil Engineering and Architecture Bldg.	177	5.6	01F*	333	330	257
				09F	908	728	640
MYK	Miyako City Hall	188	4.8	01F	138	122	277
				07F	246	197	359
				GL*	174	174	240
IWK	Iwaki City Hall	210	5.3	B1F*	175	176	147
				09F	579	449	260
ANX	Building Research Institute	330	5.3	A01*	279	227	248
				A89	142	153	102
				BFE	194	191	136
				8FE	597	506	344
				MBC	203	206	152
				M8C	682	585	311
SIT2	Saitama Shintoshin Government Office Building No.2 Annex (high-rise)	378	4.4	B3F*	74	63	42
				10FS	119	138	62
				27FS	248	503	107
SITA	Saitama Shintoshin Government Office Building, Public Welfare Building	378	4.5	01F*	90	105	47
NMW	National Museum of Western Art (base-isolation)	382	4.8	GL*	265	194	150
				B1FW	100	79	84
				01FW	76	89	87
				04F	100	77	90
CGC	Central Government Office Bldg. No.6 (high-rise)	386	4.4	01F*	90	86	45
				20B	208	148	173
				19C	179	133	130
CG2	Central Government Office Bldg. No.2 (high-rise)	386	4.2	B4F*	75	71	49
				13F	137	113	72
				21F	121	131	104
CG3	Central Government Office Bldg. No.3 (base-isolation)	386	4.5	B2F*	104	91	58
				B1F	55	41	62
				12F	94	82	104
				B8F	61	88	53
NDLA	Annex, National Diet Library	387	4.5	B4F	68	101	56
				01F*	76	104	84
				04F	125	192	94
				01F*	35	33	80
SKS	Sakishima Office, Osaka Prefecture (high-rise)	770	3.0	18F	41	38	61
				38F	85	57	18
				52FN	127	88	13
				52FS	129	85	12

Note: _: epicentral distance; I_{MA}: instrumental seismic intensity (calculated from records of acceleration of three components according to JMA method using asterisked sensor); Installation azimuth: clockwise direction from North; H1, H2, V: maximum accelerations in horizontal #1 (Azimuth), horizontal #2 (Azimuth + 90°) and vertical directions. A01: Ground surface A89: 89m underground

In Japan, strong-motion earthquake observations began in 1953. The BRI has also conducted building observations over a long period that dates back to this time. **Figure 3** shows which of the current BRI observation stations recorded measurements during the 2011 earthquake. As shown in **Figure 4**, the observation stations are more densely arranged in the Tokyo metropolitan area.

Table 1 shows the instrumental seismic intensity and directional peak acceleration for the main strong motion stations.

In terms of observed values, observation stations such as Sendai Government

Office Bldg. No. 2 (SND), Tohoku University (THU) and Iwaki City Hall (IWK) show high levels. In particular, the reinforced concrete structure of the Civil Engineering and Architecture building at Tohoku University was damaged and has been rendered unusable. At the time of the 1978 Miyagi earthquake that struck in June 1978, acceleration of more than 1G was recorded on the ninth floor of this building.

Long-lasting Shaking

As mentioned earlier the epicentral area

was large, and since there was a long time from the start to end of rupturing at the epicenter, the shocks felt in all regions continued for longer than ever before.

Table 1 shows the instrumental intensity, directional peak acceleration, etc. of the shocks recorded at major observation stations during the 2011 earthquake.

Of these stations, the Civil Engineering and Architecture building (ninth floor) at Tohoku University, which recorded a large velocity response during the 1978 off the coast of Miyagi Prefecture earthquake, also obtained a large recording this time. However, from the comparison of their respective velocity waveforms shown in **Figure 5** we can see that the 2011 earthquake was much longer than the 1978 earthquake.

In **Figure 6**, we compared the pseudo velocity response spectra that indicates the cyclical size of seismic motions for buildings in the main disaster-affected regions of Sendai, Iwaki, Miyako and Hachinohe. The observations were recorded at building ground level, basement level or on the ground. For between two and three seconds of the cycle, the observations slightly exceeded the Building Standards Law design spectra level for engineering bedrock, but not by such a large margin. In addition, observations in the long-period areas were not especially large.

Also note that at Miyako City Hall, the government building was inundated to the second floor. Since the recording device for seismological data was on the top floor of the government building, we were able to retrieve the data.

Figure 7 shows the pseudo velocity response spectra indicating the cyclical size of seismic motions for the observational data obtained in buildings in the major areas of the Tokyo metropolitan area.

Even in the Kanto region, K-NET and other networks observed extremely strong shaking at some stations in the prefectures of Ibaraki, Tochigi and Chiba.

However, observation values in the Tokyo metropolitan area itself were not that large.

Long-period Seismic Motion

Based on the size of the 2011 earthquake, strong long-period seismic mo-



Photo 1: Mid-story collapse in a low-rise building

tion was predicted, but in fact, this was not seen to a great extent in the Tokyo metropolitan area. In the Osaka Bay area, however, despite being about 770 km from the epicenter, high-rise buildings resonated at an approximate 7-second cycle due to the long-period shaking, and in one case a sway of 260 centimeters was recorded near the top of a building on the fifty-second floor. Note that even in the Tokyo metropolitan region, more than a little elevator and non-structural damage in high-rise buildings has been reported.

Damage to Buildings and Homes Due to Seismic Motion

While the 2011 earthquake was of a scale that Japan has never before experienced, buildings designed according to the new earthquake resistance standards (earthquake resistance standards introduced since June 1981) are believed to have suffered little structural damage. On the other hand, some problems have become clear. Among them the falling of non-structural materials such as ceilings was seen even in buildings designed according to the new earthquake resistance standards, and many buildings suffered damage in the form of tilting due to widespread ground liquefaction. Investigating the causes and finding solutions to these types of damage will be a major challenge in the future.

Damage to Wooden Buildings

BRI conducted a survey of damage to wooden buildings in Miyagi, Fukushima, Tochigi and Ibaraki prefectures, including in the city of Kurihara, Miyagi Prefecture, where intensity level 7 on the

seismic intensity scale was recorded. As a result, BRI confirmed significant damage in areas such as the cities of Osaki in Miyagi Prefecture and Sukagawa in Fukushima Prefecture, the town of Nasu-gun, Tochigi Prefecture and the cities of Hitachiota and Naka in Ibaraki Prefecture. On the other hand, in Kurihara, Miyagi Prefecture, which recorded level 7 on the seismic intensity scale, the damage was not so great compared with the instrumental seismic intensity that was recorded.

The types of damage observed due to seismic movement of the 2011 earthquake can be broadly categorized as either “damage attributable to shaking due to seismic motion” and “damage attributable to ground deformation.”

As forms of damage due to seismic

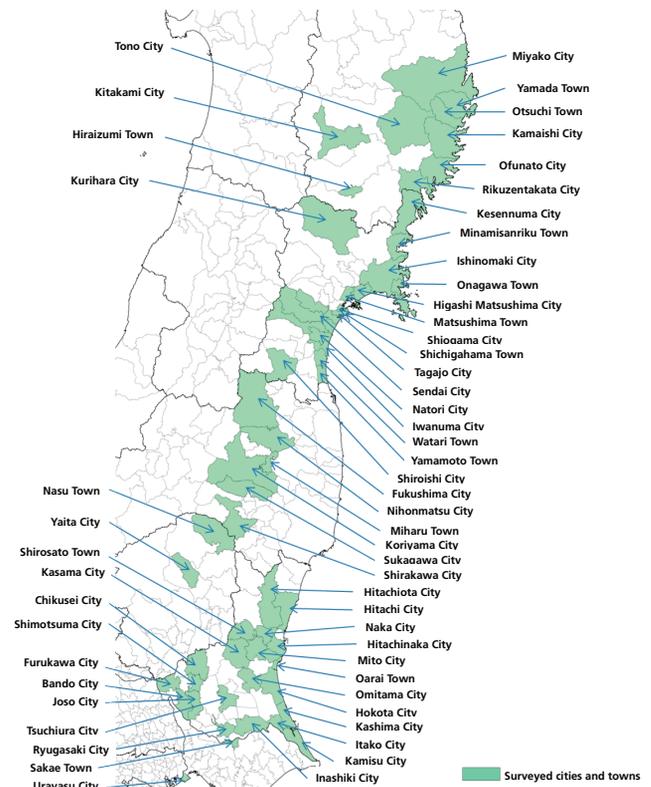


Photo 2: Fallen parts of exterior walls



Photo 3: First-floor story collapse

Figure 8: Location of surveyed cities and towns



motion, this includes roofing tile damage such as falling bricks or tiles, damage to interior materials and exterior walls (Photo 2), tilted buildings and story collapses (Photo 3). These forms of damage are largely consistent with the damage seen in past earthquakes.

As for damage due to ground deformation, multiple cases of damage to foundations and wall surfaces associated with the breaking up of the ground or retaining walls and the tilting or collapse of buildings were observed. In addition, since we observed many cases of significant damage on residential land built upon lowland swamp or filled-in rice paddies, we believe it is possible that the soft ground amplified the seismic motion.

Damage to Buildings of Steel Frame Construction

BRI conducted an exterior survey of damage to general buildings of steel frame construction such as office buildings in Miyagi, Fukushima and Ibaraki Prefectures. In addition, BRI conducted damage surveys of structures such as school gymnasiums designed according to the old earthquake resistance standards



Photo 4: Damage to exposed column bases

across a widespread area in Ibaraki Prefecture where intensity 5-upper to 6-upper shocks were observed.

In the exterior survey damage to general buildings of steel frame construction, we observed several cases of damage to the bracing structures of buildings such as parking lots, such as buckling of the bracing materials or damage to the bracing joints. Damage to the exposed column bases of parking lots was also observed (Photo 4). In the scope of this survey, no cases of critical damage such as fracture of major structural components like columns and beams were observed.

In the damage survey of school gymnasiums, etc. in Ibaraki Prefecture, we observed (i) buckling and fracture of vertical braces and fracture of joints (Photo 5); (ii) buckling in the diagonal bracing of lattice columns (Photo 6); (iii) damage to the joints between reinforced concrete columns and the roof (bearing support parts); (iv) curvature, buckling and frac-



Photo 6: Buckling of diagonal bracing of lattice columns (part shown with yellow dotted line)

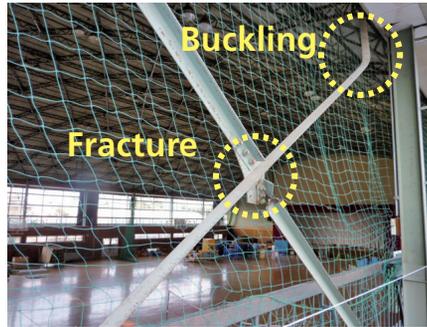


Photo 5: Buckling of bracing materials and joint fracture

ture of roof horizontal bracing; (v) cracking of column base concrete; and (vi) other damage (overturning of floor strut, etc.). However, the proportion of structures that suffered significant structural damage such as fractured vertical bracing or joint fractures can be considered low compared with the results^{*1} of a similar survey conducted at the time of the 2004 Mid-Niigata Prefecture Earthquake.

Damage to Reinforced Concrete Buildings, etc.

We conducted a damage survey of reinforced concrete (RC) buildings and steel reinforced concrete (SRC) buildings, mainly in the urban areas of regions where stations recorded seismic intensities of 6-lower and over in Iwate, Miyagi, Fukushima and Ibaraki Prefectures.

Considering the large seismic intensities observed in each area, we generally found that structural damage was not so heavy. However, in areas such as Wakabayashi Ward in Sendai and the city of Sukagawa on land that was once rice paddies and moats, a relatively higher concentration of structural damage was seen. Based on this, we believe it is possible that ground conditions had something to do with the damage that occurred.

Most of the structural damage seen in this survey was largely consistent with earthquake damage observed in the past. For instance, major damage such as mid-floor collapses in low-rise buildings (Photo 1), first-floor collapses (Photo 7) of soft first-story piloti structures and column shear failure due to loss of vertical load carrying capacity (Photo 8) also occurred, but most of the structures

which suffered damage were buildings designed according to the old earthquake resistance standards. On the other hand, very few buildings designed according to the current earthquake resistance standards suffered damage, although in some SRC buildings, damage such as buckling in the main reinforcements near base plates at the bottom of columns, shear cracks at the beam-column joints or horizontal cracks at the concrete placing joints were seen. At housing complexes in particular, we also observed many cases where shear failure occurred with non-structural walls around entrances and veranda-side mullion walls (Photo 9), and this occurred irrespective of whether old or current earthquake resistance standards had been adopted.

In the 2011 earthquake, despite the fact that there was relatively less major structural damage, we did see cases where public buildings such as city halls constructed according to the old earthquake resistance standards had suffered damage to the extent that they could not



Photo 7: Floor collapse on the first floor of a piloti structure



Photo 8: Shear failure



Photo 9: Non-structural shear failure

be used. These buildings are supposed to function as bases of operation during an emergency, and the loss of those functions may serve to again highlight the need for earthquake retrofitting.

Damage to Residential Land and Ground

In the 2011 earthquake, building damage due to ground liquefaction occurred mainly in the bay area of the Kanto region. In our survey, we observed the widespread occurrence of damage such as sand boiling and ground deformation associated with liquefaction in the alluvial plain area along the Tone river on the border between Ibaraki and Chiba Prefectures and in the city of Urayasu, Chiba Prefecture. Buildings with severe tilting (Photo 10) were also seen, but within the scope of our survey, we did not observe cracked or damaged foundations from the exterior.

In Miyagi, Fukushima and Tochigi Prefectures, significant damage (Photo 11) associated with sliding of the soil occurred mainly in developed housing areas (at their periphery in particular). In some areas we saw that deformation occurred again on developed land that had been damaged by past earthquakes. There was also a case on residential land which suffered significant damage where the soil under the foundations had slid away, but where the foundations were still holding together.

Damage to Nonstructural Components

In buildings which did not suffer major

structural damage such as story collapse, damage to exterior walls, curtain wall structures, openings and other non-structural materials was observed.

We observed extensive damage associated with exterior walls and curtain wall structures, including the shedding of exterior tiles from RC walls and the dropping of things like outer wall panels (Photo 12). We observed many buildings in which the glass from glass openings had broken. In gymnasiums, interior materials had been damaged or had fallen from the interior walls of the arena, and from the interior materials above the stage. The ceilings of gymnasiums built using a variety of construction techniques were also damaged, with the severity of damage ranging from small-scale damage along the edges to large-scale damage where entire ceilings fell down. At an airport terminal building where the lobby ceiling had fallen down (Photo 13), we observed that the layout of the roof and ground below was uneven and complicated.

As for damage to non-structural components, those built with relatively old construction methods suffered the most damage, and we also observed that non-structural components placed



Photo 10: Tilting due to liquefaction



Photo 11: Damage due to a landslide from a sloped edge



Photo 12: Fallen exterior wall panels



Photo 13: Fallen ceiling at an airport departure lobby (yellow dotted line indicates where the ceiling droppage occurred)

higher suffered relatively more damage and falling.

Concluding Remarks

Considering the size of the earthquake and the instrumental seismic intensity recorded at various locations, the damage to building structures due to seismic movement was relatively little. However, the degree of damage to buildings designed according to the old earthquake resistance standards was greater. Looking ahead, it will be necessary to review technical standards, including measures to deal with ceiling collapses and ground liquefaction, which became significant problems in the 2011 earthquake.

Finally, we would like to express our deepest condolences to those who lost their lives in the tsunami and earthquake and to their families, and offer our heartfelt sympathies to everyone affected by the disaster. 11

Note: *1 NILIM/BRI: Report on the Damage Investigation of Buildings Due to the Mid Niigata Prefecture Earthquake in 2004, pp.305–353, October, 2006 (in Japanese)