BRIEF REVIEW OF BUILDING DAMAGE BY THE 2011 TOHOKU JAPAN EARTHQUAKE AND FOLLOWING COPING ACTIVITIES

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Abstract

The 2011 Tohoku Japan earthquake of moment magnitude (Mw) 9.0 generated large ground motion and gigantic tsunami in Tohoku and Kanto areas of the northeastern part of Japan together with long-period ground motion in Osaka city. This earthquake occurred at the boundary between the North American and Pacific plates resulted in people death of 19,213 (including missing) and totally collapsed houses of 128,525 as of 27 January 2012. The hypocentral region is widely located off the coast of the prefectures of Iwate, Miyagi, Fukushima and Ibaraki with approximately 450km in length in the NS direction and 150km in width in the EW direction and the distance from these prefectures to the fault plane is almost the same, thus the places with the seismic intensity of 6- or more according to the Japan Meteorological Agency widely spread in these prefectures which resulted in damages of many buildings and residential land. Simultaneously generated tsunami attacked the coast lines of Tohoku and Kanto areas producing devastating damages.

Firstly, brief review of the building damage is presented which is based on the research and reconnaissance reports and papers by the authors and others[3]. Several key issues to be coped with by the building code are identified. They are (1) long-duration and long-period ground motion associated with mega-earthquake and seismic design of high rise and base isolated buildings, (2) seismic design and detailing of ceiling in spatial structures, (3) seismic design and detailing of escalator in shopping centers, (4) countermeasures on subsidence and inclination of residential land, (5) design of tsunami evacuation buildings, and so on. Then, the state of the on-going coping activities on each issue is introduced at the moment of a year and 9 months after 3.11 events.

Introduction

The 2011 off the Pacific coast of Tohoku earthquake (Tohoku Japan earthquake) of moment magnitude (Mw) 9.0 occurred at 14:46 JST on March 11, 2011 and generated large ground motion and gigantic tsunami in Tohoku and Kanto areas of the northeastern part of Japan. By this earthquake, people death including missing reached 19,213 and totally collapsed houses reached 128,525 according to the Japan's National Police Agency as of January 27, 2012. The Building Research Institute (BRI) and the National Institute for Land & Infrastructure Management (NILIM) sent 43 teams in total for field survey and summarized three damage reports (BRI and NILIM 2011a, 2011b, 2012). So as to reflect lesson learnt from the earthquake to practices such as the revision of building structural codes, the BRI and the NILIM are collaboratively carrying out coping activities on picked up issues with the help of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

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[3] *for example,* Nishiyama, I., et al. (2011). "Building damage by the 2011 off the Pacific coast of Tohoku earthquake and coping activities by NILIM and BRI collaborated with the administration." Pre-proceedings of 43rd Joint Meeting of United States – Japan Panel on Wind and Seismic Effects, UJNR.

Recorded Ground and Building Motions

The strong motion network (BRI Strong Motion Network Website) established in 1957 covers currently buildings in major cities across Japan. When the Tohoku Japan earthquake occurred, 58 strong motion instruments started up from Hokkaido to Kansai areas. Among them, 31 buildings including three seismically isolated buildings suffered a shaking with the seismic intensity of 5- or more by the Japan Meteorological Agency.

Strong Motion Records of Damaged Buildings. At least 4 buildings suffered severe earthquake motions with some damage. One example of the damaged buildings is the 9 storied steel reinforced concrete building in Sendai city. This building has a long history of recording of strong motions. Among them, strong motion records on the ninth floor that were obtained during the 1978 Miyagi-Ken-Oki earthquake are well known to have exceeded a maximum acceleration of more than 1000cm/s^2. By that earthquake, multi-story shear walls suffered shear crack and later repaired to behave in a ductile manner. In the meantime, during the Tohoku Japan earthquake, the repaired multi-story shear walls suffered flexural failure. Figure 1 shows the records of the strong motions and the fundamental natural periods of the building (T) calculated every 10 seconds (Kashima and Kitagawa 2005). T increased from 0.6 seconds to 1.5 seconds during the earthquake, which clearly shows and is consistent with the building damage. After the earthquake, free access to all the recorded digital data including those of this building is strongly requested even from oversea researchers.

Long-period Earthquake Ground Motions in Osaka Bay. During the Tohoku Japan earthquake, long-period earthquake ground motions with long duration were observed in Tokyo, Osaka and other large cities. One example is the 52+3 storied steel office building on the coast of Osaka Bay that is 770 km away from the hypocenter. Figure 2 shows the records of the absolute displacement waveforms. The absolute displacements in the SW-NE and in the NW-SE directions on the 1st floor was less than 10 cm, but the 52nd floor in the building suffered a large motion with a zero-to-peak amplitude of more than 130 cm, which is thought to be due to a resonance phenomenon. This indicates the importance of the prediction of long-period ground motions by mega-earthquakes possibly to occur in Nankai trough.

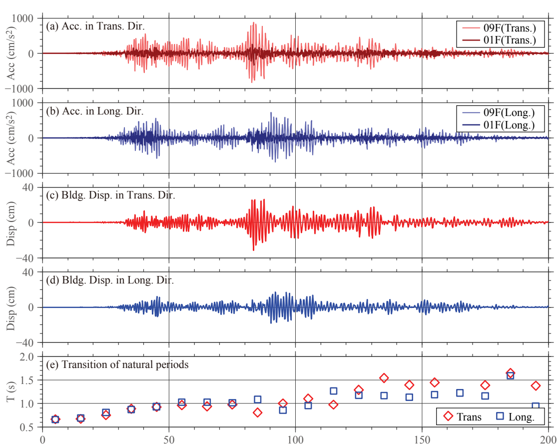


Figure 1. Recorded strong motion and the calculated fundamental natural period

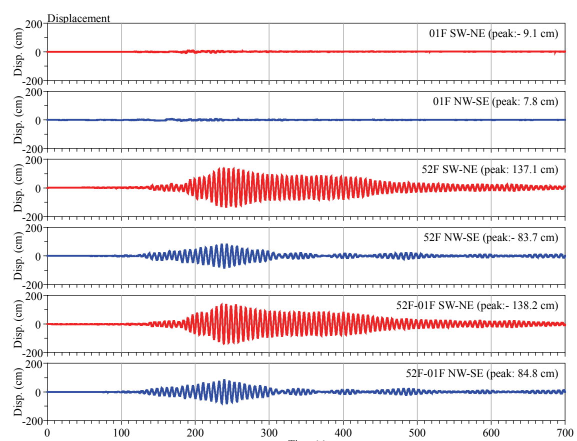


Figure 2. Recorded strong motion of 52+3 storied steel office building located 770km from the epicenter

Building and Residential Land Damage by Earthquake Motion

The Tohoku Japan earthquake brought about building damage in a wide area of various prefectures on the

Pacific coast in eastern Japan such as Iwate, Miyagi, Fukushima, Ibaraki and Chiba, and also brought about heavy liquefaction at the catchment basin area of Tone River and the reclaimed ground on Tokyo Bay, thus the BRI and the NILIM selected the locations of the reconnaissance study (field survey) as shown in Figure 3 with the exception of the area near the Fukushima Daiichi Nuclear Power Station. The field surveyed results are detailed in the reports (BRI and NILIM 2011a, 2011b, 2012).

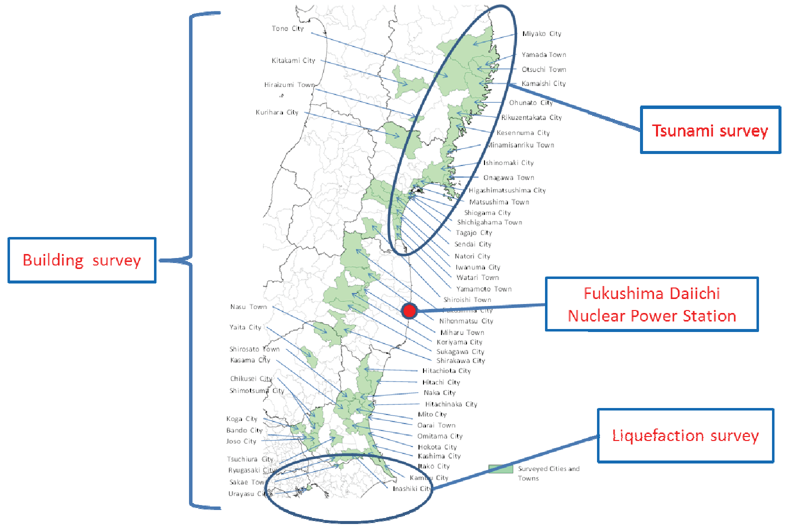


Figure 3. Locations of field surveyed cities and towns by the BRI and the NILIM

Building Damage by Earthquake Motion. *Wood houses* - Most of the patterns of the damages to the wood houses were observed in past destructive earthquakes. *Steel buildings* - Steel gymnasiums are surveyed extensively in Ibaraki prefecture, as the structural system of them is similar to that of factories and warehouses which are hard to be surveyed as they are private property. Most of the patterns of the damages were observed in past earthquakes, while the spalling of concrete at the joint of the steel roof structure and the reinforced concrete column shown in Figure 4 and the fallen down of ceiling shown in Figure 5 were marked. *Reinforced concrete buildings* - Most of the patterns of the damages to reinforced concrete buildings were observed in past destructive earthquakes. So-called emergency operation buildings like city halls survived, but were not operational as shown in Figure 6, which implies the necessity of higher level of performance in such buildings. Damage to the nonstructural walls adjacent to the door of residential buildings shown in Figure 7 causes the similar problem. The retrofitted buildings behaved well in general with some exception. *Seismically isolated buildings* - Sixteen seismically isolated buildings in Miyagi prefecture and one in Yamagata prefecture were surveyed in which three buildings were instrumented and recorded strong motions. All of these buildings performed structurally very well and the steel dampers absorbed earthquake energy by the plastic deformation. However, the lead dampers suffered cracks due to many cycles of small amplitude of reversed deformation as shown in Figure 8. Damage to the expansion joints was also seen quite frequently, which can be improved very soon. *Residential land* - In the catchment area of Tone River and the coastal zone of Tokyo Bay, extensive damage such as sand boiling or ground transformation associated with liquefaction was confirmed. Highly tilted buildings were seen, but visual cracks on the foundations were not observed as shown in Figure 9. In Sendai city, the ground transformation by sliding of the housing site embankment was observed just like the one after the 1978 earthquake.

Figure 4. Spalling of concrete

Figure 5. Fallen down of ceiling

Figure 6. Survived but not functional

Figure 7. Nonstructural wall failure

Figure 8. Lead damper cracked

Figure 9. Tilted house by liquefaction

Building Damage by Tsunami. The coastal area along Aomori prefecture to Miyagi prefecture shown in Figure 3, where northern part is ria coast and southern one is coastal plain, was surveyed. First, the building damage by tsunami was classified into several damage patterns from the field survey. Next, about 100 buildings are carefully selected and studied in details such as on the dimension of the structure of the building, the maximum inundation depth at the building from the tsunami traces, damages of the building and so on, which were used in the study on tsunami evacuation buildings. Damage patterns by tsunami were classified as follows; 1) complete washed away, 2) overturning with the effect of buoyancy, 3) tilting after scouring, 4) damage by debris impact, and 5) survived from tsunami by shading effect of front buildings. They are shown in Figs. 10 - 14.

Figure 10. Complete washed away

Figure 11. Overturning

Figure 12. Tilting by scouring

Figure 13. Debris impact

Figure 14. Shading effect by front building

Coping Activities on Issues

From the study and the survey explained above, the following issues were picked up. The coping activities, with the help of the MLIT, had been started and are still underway by the BRI and the NILIM. The research results are planned to be reflected to the revision of the building structural codes, which will be proposed by the NILIM after taking into account the expert opinions by the Building Structural Codes Committee as shown in Figure 15.

- Possibility of free access to the digital data recorded by the BRI strong motion network (is under consideration in the BRI, consulting with owners of the instrumented buildings, etc.)
- Prediction of long-period earthquake ground motion for design use, together with re-evaluation of structural performance under multiple cycles of loadings
- Higher level of performance based design so as to reduce those buildings, which survived but not functional after earthquake (will be studied in the BRI)
- Addition to the building structural codes to deal with the problems of fallen down of ceilings and so on
- Evaluation of residual structural performance of fractured lead damper in seismically isolated buildings (was conducted by the Japan Society of Seismic Isolation)
- Liquefaction countermeasure for residential houses, for which neither structural calculation nor soil investigation is mandatory
- Evaluation of tsunami force necessary for the design of tsunami evacuation buildings

Long-period Earthquake Ground Motion. A social concern on the long-period earthquake ground motions by mega-earthquakes at the subduction zone near ocean trench had been raised since the occurrence of oil tank fire during the 2003 Tokachi-Oki earthquake, and the prediction maps were announced based on detailed calculation (Headquarter for Earthquake Research Promotion Website 2009, 2012). However, the prediction just includes the components of motions with the period longer than 2.0 second and so the higher mode response of the buildings cannot necessarily be represented. Moreover, the prediction could not predict an earthquake not experienced and does not include the combined mega-earthquakes such as the Tonankai-Nankai earthquake for instance.

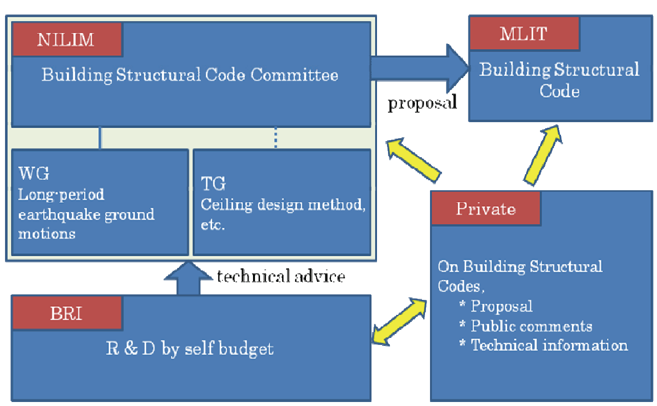


Figure 15. Building Structural Codes Committee in NILIM

The BRI and the NILIM with the collaboration of the MLIT adopted much practical empirical prediction method (Okawa, et al. 2010) based on the observations at about 1,600 recording stations across Japan, the result of which had been released in December 2010 by the NILIM and the MLIT and received several hundreds of public comments. After the Tohoku Japan earthquake, numbers of high quality recorded data became available and additional validation studies on the empirical prediction method taking into account the location of epicenters and the paths were carried out. Finally, revised evaluation method was proposed. Figure 16 shows the predicted velocity response spectrums by the revised evaluation method for Nankai trough three-connected earthquake model. On August 29, 2012, it was announced officially the mega-earthquake model in Nankai trough (Cabinet Office 2012), but the Headquarters for Earthquake Research Promotion has not yet completed the calculation of expected long-period ground motion as of November, 2012.

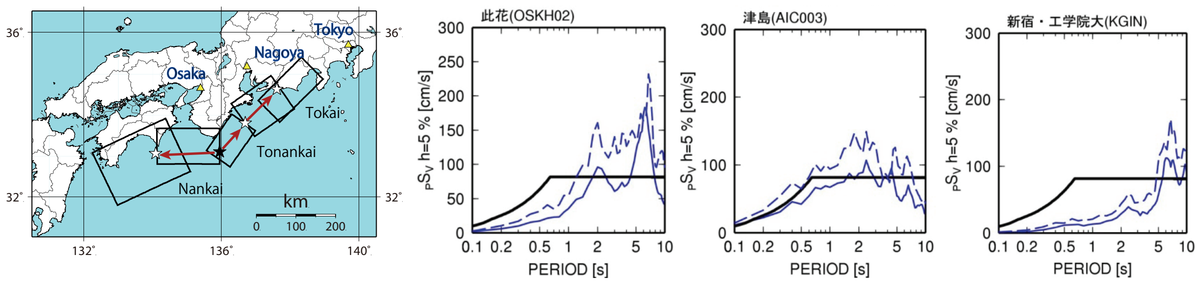


Figure 16. Nankai trough three-connected earthquake source model (left), predicted velocity response spectrum at Osaka, Nagoya and Tokyo (right)

Fallen Down of Ceilings and so on. The problem of fallen down of the ceilings which cover large space such as gymnasiums has been indicated by the BRI and the NILIM since 2001 Geiyo earthquake, and technical advice to install appropriate amount of diagonal braces on hanging bolts and to keep appropriate clearance between ceiling and surrounding structure have been announced from the MLIT. In the Tohoku Japan earthquake, huge number of large space ceilings (about 2,000) fell down and even casualties occurred. Therefore, extensive detailed survey on ceilings fell down during the earthquake was restarted, where 151 damaged ceilings are collected and 11 of them were studied in detail. Based on this study in addition to the previous knowledge, the current qualitative technical advice is planned to be modified into much quantitative one. Figure 17 compares the ceiling height and unit mass of the fell down ceiling with the cases of with and without injury.

Fallen down of the escalator trusses in shopping centers were reported on October 26, 2011 by mass media. In ordinal practices, overlapping between the escalator truss and the girder on the upper story is selected as H/100+20mm, where H is the height of the escalator. Currently, the requirement of overlapped length is planned to be increased with the exceptions with fall prevention device as shown in Figure 18.
Figure 18 Comparison of liquefaction evaluation and observation results

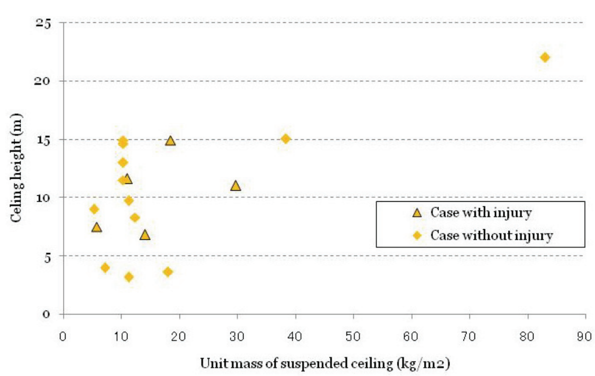


Figure 17. Fall down of ceilings and with/without injury

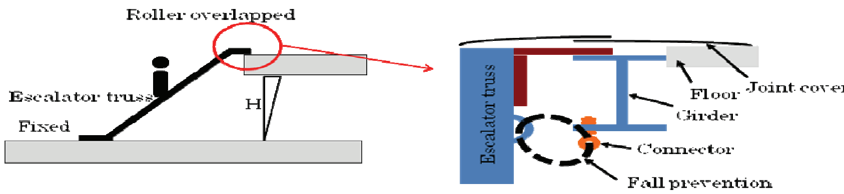
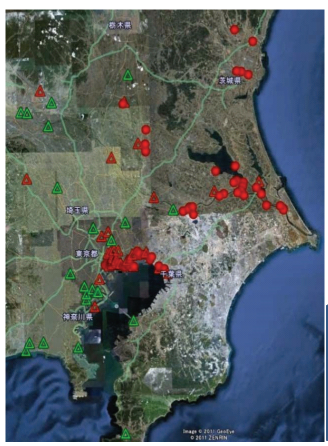


Figure 18. Prevention of fallen down of escalator truss

Liquefaction Countermeasure for Residential Houses. For wood houses, the structural calculation is not mandated in the Japan's Building Standard Law. Thus, the liquefaction countermeasures cannot be considered at present in the building construction for the detached houses.

The 112 sites are selected in Kanto area and carried out liquefaction evaluation at each site by F_L-method (Japan Road Association 2002), and the results were compared with the observation as shown in Figure 19. All liquefied sites were predicted, but still many sites without liquefaction were cautioned, which requires the further improvement of evaluation accuracy. So as to apply F_L-method, N-value by SPT (standard penetration test), fine fraction content, water level, and so on are needed. The cost necessary for getting these information is not affordable for the owner of residential house, thus the BRI is now trying to study the possibility of only using SWS (Swedish weight sounding test) plus water level and soil judgment, instead. Study on development of countermeasure techniques applicable for existing buildings is also underway.



	Liquefied sites	Non-liquefied sites
$F_L \leq 1$	53 ●	35 △
$F_L > 1$	0 ●	24 △

Figure 19. Comparison of liquefaction evaluation and observation results

Tsunami Evacuation Buildings. As for the design of buildings against tsunami force, the guidelines for tsunami evacuation buildings (Cabinet Office 2005) are the unique technical information previously. These guidelines are established as part of the countermeasures for Tonankai-Nankai earthquake provided by the Central Disaster Management Council. In the guidelines, the tsunami force is considered to be equivalent static water pressure as shown in Figure 20 (left) where the static water pressure of 3 times of the inundation depth is considered including the tsunami dynamic force. Here, 3 is the coefficient of water depth proposed by the waterway model test (Asakura, et al. 2000).

As explained above, about 100 buildings were carefully selected and studied in detail. First, the horizontal resistant strength of each building is evaluated whether damaged or not from the surveyed dimensions. Next, the coefficient of water depth is calculated so that the tsunami horizontal force estimated considering the observed inundation depth at or around the building as a function of the coefficient agrees with the calculated building strength. Figure 20 (right) shows the relation of tsunami inundation depth and the estimated coefficient for the studied buildings. It can be seen that the coefficient of water depth is about 1.0 and it reduces as the inundation depth increases shown by dotted lines. In the tentative guidelines announced from the MLIT in December 2011, the coefficient of water depth was relaxed as 2.0 in case the building was blessed by the shading effect from front building and/or embankment and further relaxed as 1.5 in case the building located at 500m or larger from the coastline and river in addition to shading effect as shown by dashed lines.

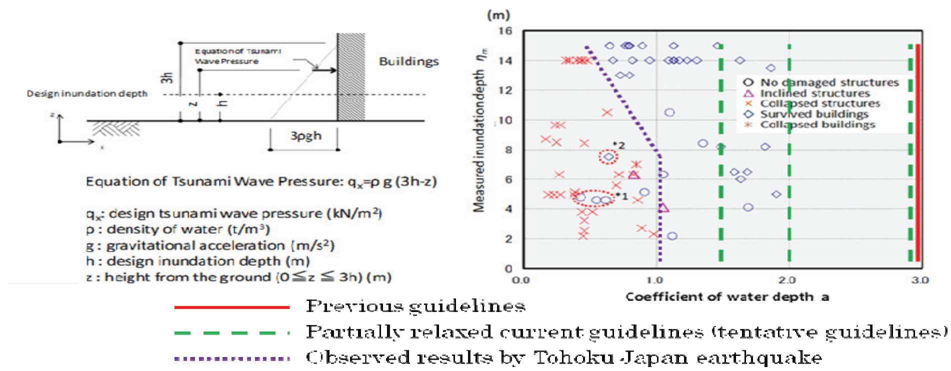


Figure 19. Estimated coefficient of water depth of detailed studied buildings

The BRI worked with Kajima Co. and U. of Tokyo and conducted waterway experiment in 2012, and improved CFD (Computational Fluid Dynamics). In future, the improved CFD technique for evaluation of tsunami pressure on buildings will be used to increase the accuracy of the effect of openings, the effect of water infiltration and so on, which can further relax the design of tsunami evacuation buildings.

Conclusions

The BRI and the NILIM collaborated in the process of the recorded strong motions in and around instrumented buildings and also in the field survey of damaged buildings and residential land by the Tohoku Japan earthquake. In this paper, the brief review of the collaborated work is presented first and then the state of the on-going coping activities on selected issues is presented such as long-period earthquake ground motion, fallen down of ceilings and escalators, liquefaction countermeasure for residential houses, and tsunami evacuation buildings.

Acknowledgments

The authors wish to express their gratitude to the members of the BRI and the NILIM who served for data analyses of observed strong motions and field surveys of earthquake and tsunami damage of buildings and residential land, and to those of the building users/owners who allow site surveys under severe restoration conditions. Finally, the authors would like to express our deepest condolences to those who lost their families and those who are suffering from the disaster until this moment.

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