Brief Review of Building Damage by The 2011 Tohoku Japan Earthquake and Following Activities for Disaster Mitigation

by

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ABSTRACT

The 2011 Tohoku Japan earthquake generated large ground motion and gigantic tsunami in Tohoku and Kanto areas of the northeastern part of Japan. Since the hypocentral region is widely located off the coast of Japan, damages of many buildings and residential land by earthquake motions and devastating damages by tsunami attack occurred. The brief review of the building damages is presented, based on the research and reconnaissance reports of the Building Research Institute (BRI) and the National Institute for Land & Infrastructure Management (NILIM). Research Acitivities according to damages and seismic behaviors of buildings for disaster mitigation, such as prediction of long-duration and long-period earthquake ground motion for design use, problems of ceilings, liquefaction countermeasure for residential houses, and countermeasure for tsunami force are introduced.

KEYWORDS: 2011 Tohoku Earthquake, Building Behavior, Building Damage, Research Action, Disaster Mitigation

1. INTRODUCTION

The 2011 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. 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 with approximately 450km in length in the NS direction and 150km in width in the EW direction gave the seismic intensity of 6- or more according to the Japan Meteorological Agency (JMA). As a result, damages of many buildings and residential land by earthquake motions and devastating damages by tsunami attack occurred in the coast lines of Tohoku and Kanto areas.

The BRI and the NILIM sent 43 teams in total for field survey and summarized three damage reports [1, 2, 3]. 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 administration by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

In the paper, brief review of the building damage is presented which is based on the research and reconnaissance reports. Several key issues to be coped with by the building structural codes are identified. They are 1) prediction of long-duration and long-period earthquake ground motion for design use, 2) problems of fallen down of ceilings and so on, 3) liquefaction countermeasure for residential houses, 4) evaluation of tsunami force, etc. Then, the state of the on-going coping activities on each issue is introduced at the moment of a year and 10 months after the earthquake.

2. RECORDED GROUND AND BUILDING EARTHQUAKE MOTIONS

2.1 Strong Motion Network of Building by BRI

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The strong motion network (BRI Strong Motion Network Website [4]) established in 1957 covers currently more than 70 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 JMA seismic intensity of 5- or more. After the earthquake, free access to all the recorded digital data is strongly requested even from oversea researchers.

2.2 Strong Motion Record of Damaged Building

At least 4 buildings suffered severe earthquake motions with some damage. One example of the damaged buildings is a 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 [5]. The T increased from 0.6 seconds to 1.5 seconds during the earthquake. The change of T clearly shows and is consistent with the building damage.

2.3 Long-period Earthquake Ground Motion

During the Tohoku Japan earthquake, long-duration and long-period earthquake ground motions 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 and relative 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-duration and long-period ground motions by mega-earthquakes possibly to occur in Nankai trough.

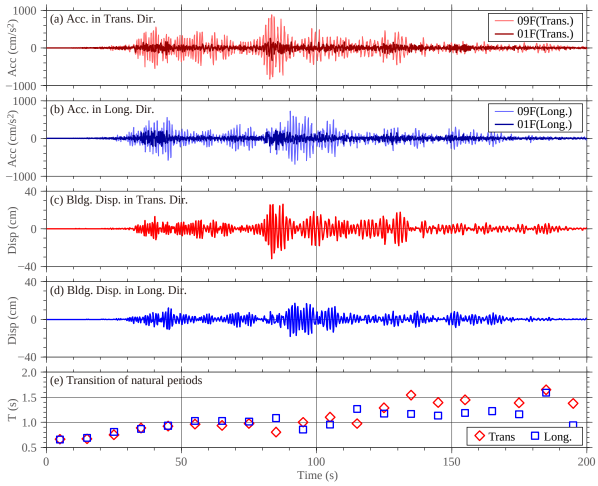


Fig. 1 Recorded strong motion and the calculated fundamental natural period

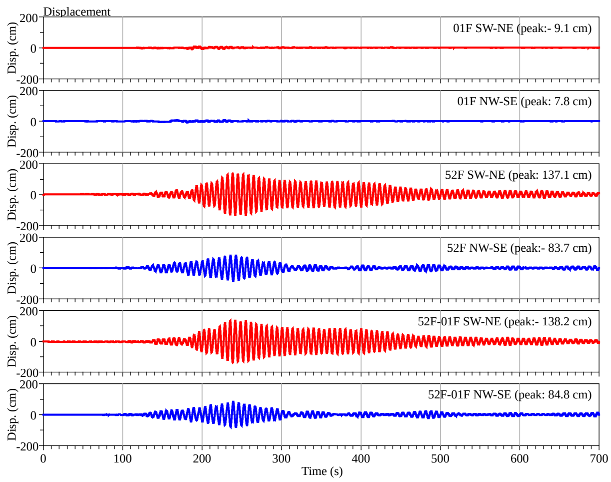


Fig. 2 Recorded strong motion of 52+3 storied steel office building located at 770km from the epicenter

3. BUILDING AND RESIDENTIAL LAND DAMAGE

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

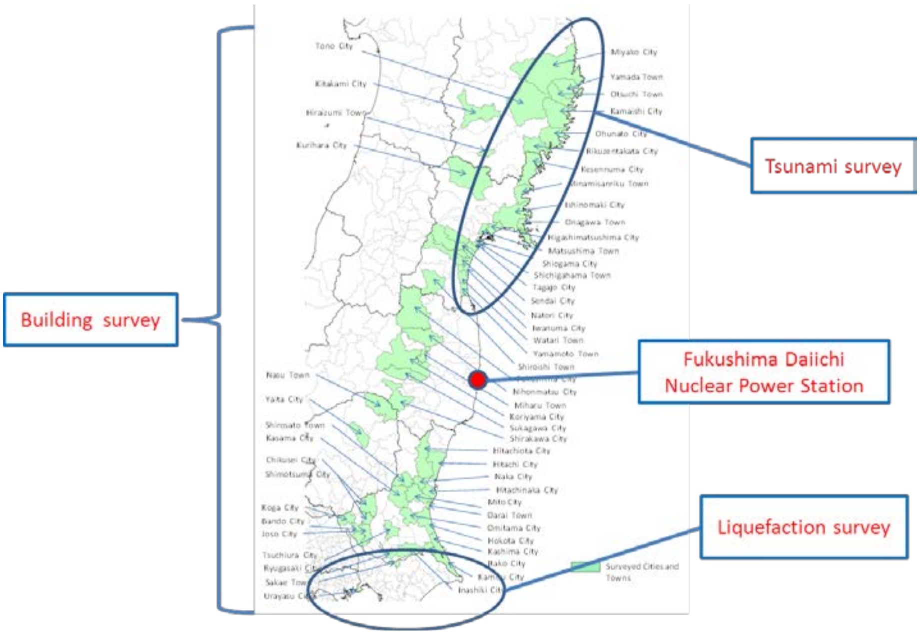


Fig. 3 Locations of field surveyed cities and towns by the BRI and the NILIM

and the NILIM selected the locations of the reconnaissance study (field survey) as shown in Fig. 3 with the exception of the area near the Fukushima Daiichi Nuclear Power Station. The field surveyed results are detailed in the reports [1, 2, 3].

3.1 Building Damages by Earthquake Motion

1) Wood houses: Most of the patterns of the damages to the wood houses were observed in past destructive earthquakes.

2) 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 Fig. 4 and the fallen down of ceiling shown in Fig. 5 were marked.

3) 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 offices survived, but were not operational as shown in Fig. 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 Fig. 7 causes the similar problem. The retrofitted buildings behaved well in general with some exception.

Fig. 4 Spalling of concrete

Fig. 5 Fallen down of ceiling

Fig. 6 Survived but not functional

Fig. 7 Nonstructural wall failure

4) 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 Fig. 8. Damage to the expansion joint was also seen quite frequently, which can be improved as early as possible.

Fig. 8 Lead damper cracked

5) 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 residential houses were seen, but visual cracks on the foundations were not observed as shown in Fig. 9. In Sendai city, the ground transformation by sliding of the housing site embankment was observed just like the one after the 1978 Miyagi-Ken-Oki earthquake.

Fig. 9 Tilted house by liquefaction

3.2 Building Damages by Tsunami

The coastal area along Aomori prefecture to Miyagi prefecture shown in Fig. 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. 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 (as shown in Fig. 10), 2) overturning with the effect of buoyancy (Fig. 11), 3) tilting after scouring (Fig. 12), 4) damage by debris impact (Fig. 13), and 5) survived from tsunami by shading effect of front buildings (Fig. 14).

Fig. 10 Complete washed away

Fig. 11 Overturning

Fig. 12 Tilting by scouring

Fig. 13 Debris impact

Fig. 14 Shading effect by front building

4. RESEARCH ACTIVITIES FOR COUNTER-MEASURE AGAINST DAMAGES

4.1 Coping Activities on Selected 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 Fig. 15.

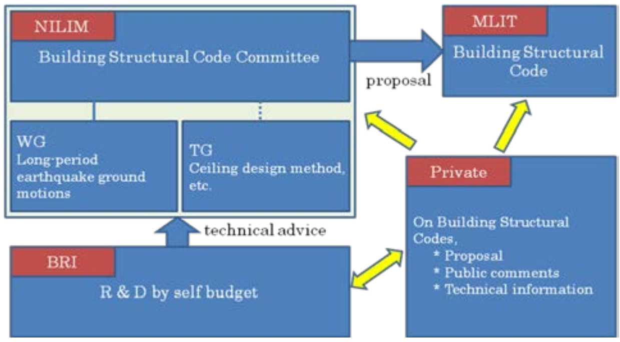


Fig. 15 Building structural codes committee in NILIM

- 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-duration and long-period earthquake ground motion for design use, together with re-evaluation of structural performance under multiple cycles of loadings
- 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

The building structural division of the MLIT supports the budget to promote the research and development for countermeasure projects and revision of the building structural code. The MLIT organized a production of promotion project for building-standards maintenance (promotion project). Many activities are going under the promotion production. When the new activity will be necessary, such as, the countermeasure against building damages, and accidents, a new item will constructed. The BRI contributes the setting theme and obtaining fruitful results with collaboration of the promotion projects

4.2 Long-duration and long-period Earthquake Ground Motion due to Next Earthquake

A social concern on the long-duration and 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 [6, 7]).

The BRI and the NILIM with the collaboration of the MLIT adopted much practical empirical prediction method [8] based on the observations at about 1,600 recording stations across Japan. A proposal of empirical prediction 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 were carried out, taking into account the location of epicenters and the paths. Finally, revised evaluation method was proposed. Figure 16 shows the predicted velocity response spectra 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 by Cabinet Office [9], but the Headquarters for Earthquake Research Promotion has not yet completed the detailed calculation of expected long-duration and period ground motion as of November, 2012.

4.3 Behavior of Super High-rise and Seismically Isolated Buildings Under Long-period Earthquake Motion

The researches on evaluating the seismic behavior of super high-rise (reinforced concrete and steel) and seismically isolated buildings under the long-duration and long-period earthquake motions with the collaboration with the promotion projects by the MLIT. The researches on characteristics of members and isolation devices have been conducted under the experiment with multi-cycle loadings.

As for the reinforced concrete structure, in addition to statically repeated loading experiments of the columns, girders and their joints, the shaking table test on a 20-story frame model of 1/4 in scale and 20m in height was carried out, as shown in Fig.17. In the shaking

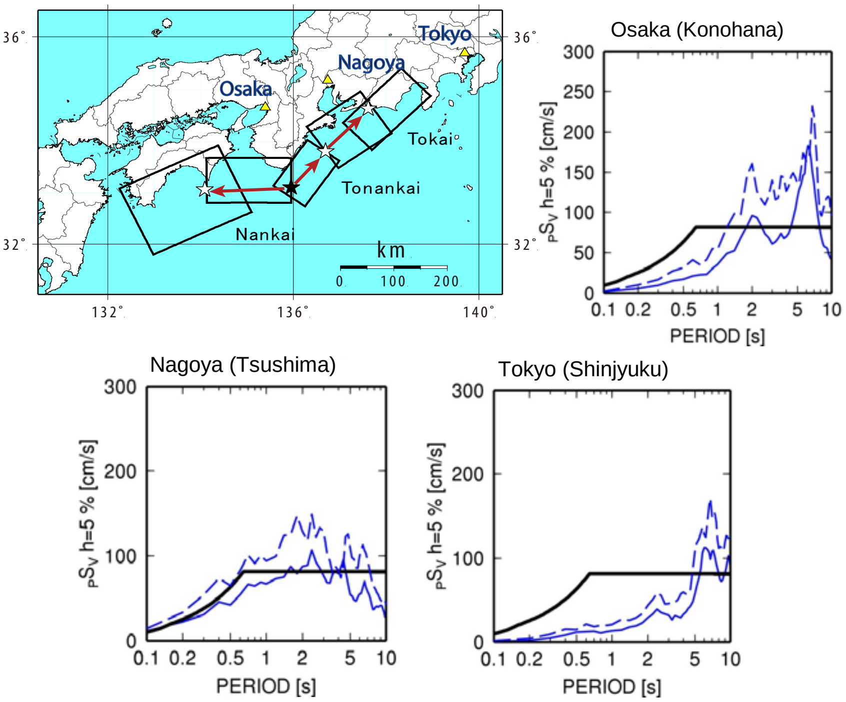


Fig. 16 Nankai trough three-connected earthquake model and predicted velocity response spectrum at Osaka, Nagoya and Tokyo

table test, the story drift angle of the model reached a large deformation of 1/37rad. The behavior of the model was quite sable under the large deformation.

As for the steel structure, the static experiments for the columns, girders and their joint panels were conducted. Based on the plastic ratio and the accumulated plastic ratio, the fatigue damage potential of the steel members is evaluated. Dynamically multi-cycled tests of isolators and dampers were conducted, as shown in Fig.18. The dependency of the input energy on the characteristics of the devices, such as, heat generation, the changes of yield force or friction force was evaluated under the multi-cyclic excitation.

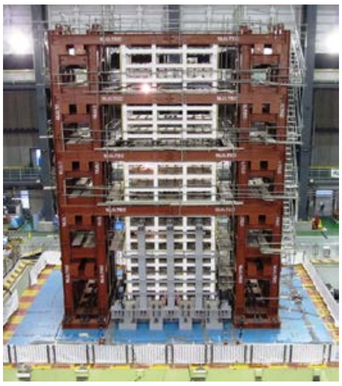


Fig. 17 Scale model of super high-rise RC building for shaking table test

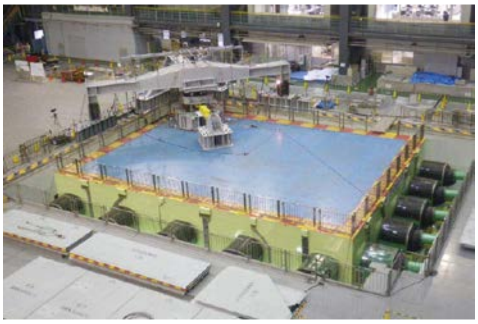


Fig. 18 Dynamically multi-cycled tests of isolators

4.4 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. The technical advice to install appropriate amount of diagonal braces on hanging bolts and to keep appropriate clearance between ceiling and surrounding structure have been recommended from the MLIT, the BRI and the NILIM. In the Tohoku Japan earthquake, huge numbers of large space ceilings (about 2,000) fell down and even casualties occurred. Therefore, extensive detailed survey on the ceiling damages was conducted, 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. Fig. 19 compares the ceiling height and unit mass of the fallen ceiling with the cases of with and without injury.

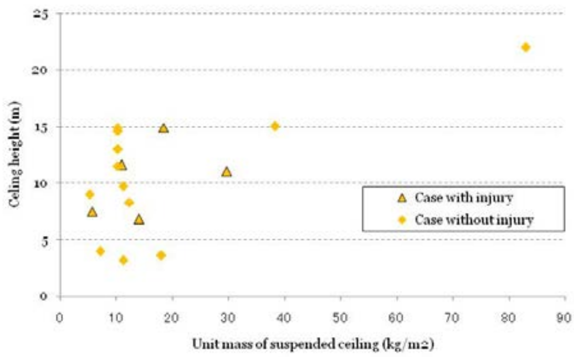


Fig. 19 Fallen ceilings with/without injury

After the earthquake, the NILIM and the BRI started to the countermeasure for improve the earthquake resistance of ceilings against the earthquake. The discussion items for improvement are specification for ceiling materials and setting, and the appropriate methods for calculating seismic response of ceiling and conditions for safety.

The 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 to H/40 with the exceptions with fall prevention device as shown in Fig. 20.

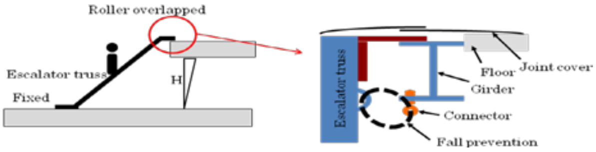
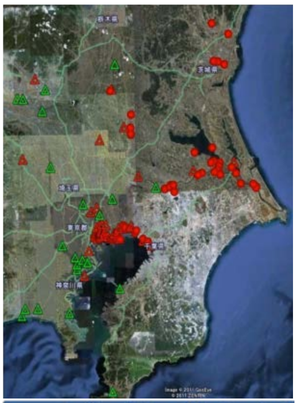


Fig. 20 Prevention of fallen down of escalator truss

4.5 Liquefaction Countermeasure for Residential Houses

For wood houses, the structural calculation is not mandated in the Japan's building structure codes. Thus, the liquefaction countermeasures is not clearly provided at present in the building construction for the detached houses.

The liquefaction evaluation by F_L-method was carried out in selected 112 sites in Kanto area [10], and the results were compared with the observation as shown in Fig. 21. All liquefied sites were predicted, but still many sites without liquefaction were cautioned. These require 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 the information is not affordable for the owner of residential house. The BRI is now trying to study the possibility of only using SWS test (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
$F_L \leqq 1$	53 ●	35 △
$F_L > 1$	0 ●	24 △

Fig. 21 Comparison of liquefaction evaluation and observation results

4.6 Tsunami Evacuation Buildings

As for the design of buildings against tsunami force, the guidelines for tsunami evacuation buildings [11] 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

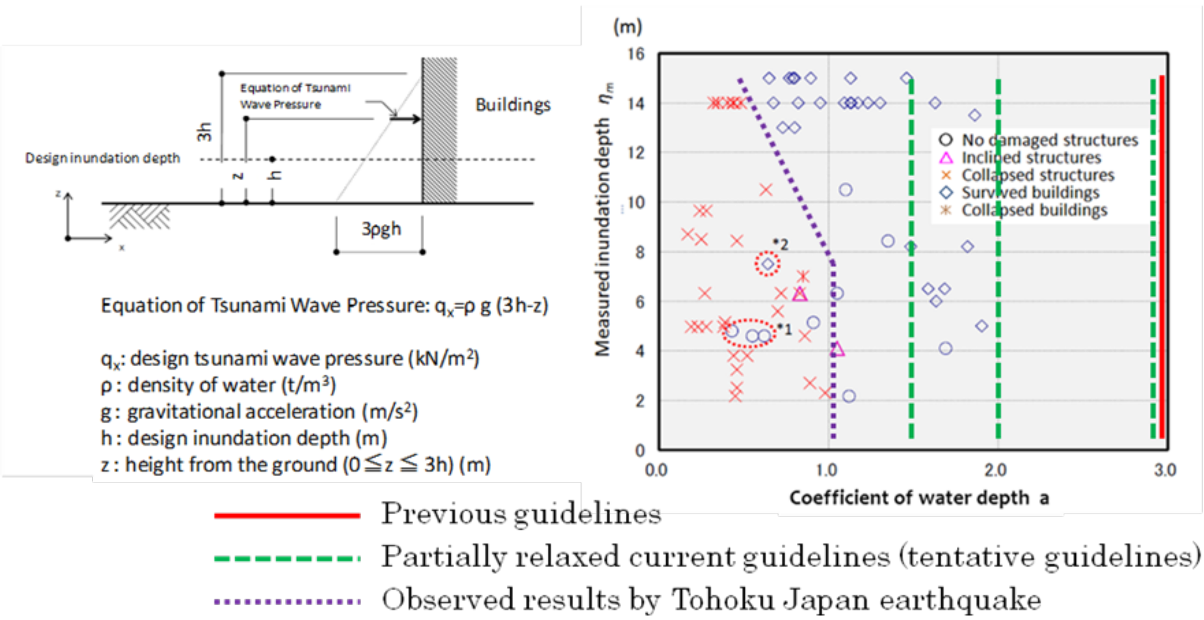


Fig. 22 Estimated coefficient of water depth of detailed studied buildings

equivalent static water pressure as shown in Fig. 22 (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 [12].

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. Fig. 22 (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 decreased by 2.0 in case the building was protected by the shading effect from front building and/or embankment. Further decreased value of 1.5 in case the building located at 500m or further from the coastline and river in addition to shading effect as shown by dashed lines is set.

The BRI worked with Kajima Co. and Univ. 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 of the buildings, the effect of water infiltration into the buildings and so on, which can further relax the design of tsunami evacuation buildings.

5. RESEARCH ACTIVITIES FOR KEEPING FUNCTION AND SEISMIC PERFORMANCE OF BUILDING

5.1 Higher level of performance for keeping function after earthquake

National and local government office buildings must be an emergency base and assist refugees and citizens just after earthquakes. But more than 10 local government buildings suffered from the 2011 Tohoku Japan Earthquake. There were damages of structural and non-structural member as shown in Fig. 23. They could not keep their function because staffs were prohibited to continuing to work inside. All of damaged buildings are designed by old building structural code, the judgment for safety or not depends greatly on the damage of non-structural members.

Fig. 23 Structural and non-structural damage of local government building

Another example is the damage of gymnasiums which must be utilized for places of refuge after earthquakes. A lot of gymnasiums suffered falling-down of ceiling (Fig. 5) and spalling of concrete at joins between steel roofs and RC columns (Fig. 4).

Because the damage on pile head of foundation as shown in Fig. 24, the super-structure tilted and the inhabitants could not continue to live in the building. The damage for buildings whose superstructure was retrofitted or strengthened was founded. These buildings will be demolished or jacked up after underpinning of piles.

Fig. 24 Structural damage of pile head

For performance for keeping functional after earthquake, it must be avoid these damages for especially facilities as the emergency base and assist refugees and citizens such as national and local government office, gymnasiums, schools, residences and so on. The required performance for these buildings will be made clear and technologies for an effective seismic retrofit will be developed.

5.2Detailed evaluation for earthquake resistance performance of buildings

On August 29, 2012, the estimation of earthquake damage by the mega-earthquake in Nankai trough was announced [9]. In the worst case, the number of completely collapsed buildings and broken buildings by fire will be about 0.95 to 2.38 million and the number of lost people will be 80 to 320 thousand.

Under the mega-earthquake, earthquake motion will be severe and the amplitude of motions will probably exceed the level of earthquake motion which is prescribed in the building structural code. Also earthquake motions observed during recent earthquakes sometimes exceeded the level in the code, as shown in Fig. 25. But severe damages in the areas were not always reported.

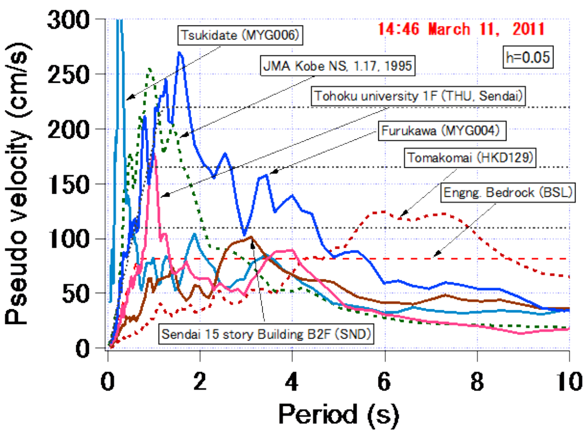


Fig.25 Pseudo velocity spectra of observed earthquake motions

In order to precisely evaluate the earthquake response and resistance of building, following items will be reviewed;

1) Dynamic soil structure interaction

Earthquake motions to building are changed by the kinematic interaction due to effects of embedment and pile foundation. Also the damping effects will be changed by radiation damping to ground through the foundation.

2) Structural modeling

More detailed modeling of structures is necessary to obtain the precise response of building. There are effects of presence of floor slab and restriction of column deformation on the response.

3) Material strength and proposed design formula

The design values of strength in every material and proposed design formula are set to a safety side. The values based on more actual characteristics must be estimated.

6. 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. The outlines of the on-going and near-future research activities for countermeasure against damages and so on are summarized.

1) Possibility of free access to the digital data recorded by the BRI strong motion network
2) Prediction of long-duration and long-period earthquake ground motion for design use and re-evaluation of structural performance under multiple cycles of loadings
3) Improvement of the seismic performance of fallen down of ceilings and so on
4) Liquefaction countermeasure for residential houses, for which neither structural calculation nor soil investigation is mandatory
5) Evaluation of tsunami force necessary for the design of tsunami evacuation buildings
6) Higher level of performance for keeping function after earthquake
7) Detailed evaluation for earthquake resistance performance of buildings

7. 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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