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BUILDING DAMAGE BY THE 2011 TOHOKU JAPAN EARTHQUAKE AND COPING ACTIVITIES BY NILIM AND BRI COLLABORATED WITH THE ADMINISTRATION

Isao NISHIYAMA[1], Izuru OKAWA[2], Hiroshi FUKUYAMA[3] and Yasuo OKUDA[4]

[1] Director, Building Department, National Institute for Land & Infrastructure management (NILIM),
Ministry of Land , Infrastructure, Transport & Tourism (MLIT), Tsukuba, Japan,
nishiyama-i92ta@nilim.go.jp
[2] Senior Research Fellow, Department of Structural Engineering, Building Research Institute (BRI),
Tsukuba, Japan, okawa@kenken.go.jp
[3] Chief Research Engineer, Department of Structural Engineering, BRI, Tsukuba, Japan,
fukuyama@kenken.go.jp
[4] Chief Research Engineer, Department of Structural Engineering, BRI, Tsukuba, Japan,
y_okuda@kenken.go.jp

ABSTRACT: This paper presents the outlines of the strong motions recorded in and around the buildings by the BRI Strong Motion Network, the motion induced building and residential land damage and the tsunami induced building damage by the 2011 Tohoku Japan earthquake. On-going coping activities in order to establish necessary technical standards collaborated with the administration are also introduced.

Key Words: 2011 Tohoku Japan earthquake, strong motion in and around buildings, earthquake and tsunami damage, buildings and residential land, coping activities related with building technical standards

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 together with long-period ground motion in Osaka city. This was a thrust earthquake occurring at the boundary between the North American and Pacific plates. This earthquake is the greatest in Japanese recorded history and the fourth largest in the world since 1900 (U.S. Geological Survey Website). As of 9 December 2011, people death reached 15,841 and totally collapsed houses reached 126,280 according to the Japanese National Policy Agency.

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 a little late producing devastating damages.

The National Institute for Land & Infrastructure Management (NILIM) and the Building Research Institute (BRI) collaborated in the process of the recorded strong motions in and around instrumented buildings and also in the reconnaissance study of buildings and residential land damaged by the earthquake and the tsunami. In this paper, the outline of the collaborated work is presented first and then the state of the on-going coping activities on selected issues in order to establish necessary technical standards. The content of this paper is based on the research and reconnaissance reports (NILIM and BRI 2011a, 2011b), and is mostly taken from the paper by the authors (Nishiyama et al. 2011).

RECORDED GROUND AND BUILDING MOTIONS

The strong motion network (BRI Strong Motion Network Website) covers buildings in major cities across Japan. When the 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.

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-story steel reinforced concrete school building of the Human Environmental Course, Tohoku University, 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 1000 cm/s2.

During the earthquake, multi-story shear walls of the building suffered flexural failure with other damage. Photo 1 and Fig. 1 show the appearance of the building and the records of the strong motion. The fundamental natural periods of the building calculated every 10 seconds (Kashima and Kitagawa 2005) increased from 0.6 seconds to 1.5 seconds during the earthquake, which clearly shows and agrees with the building damage.

Photo 1 Building of Tohoku University

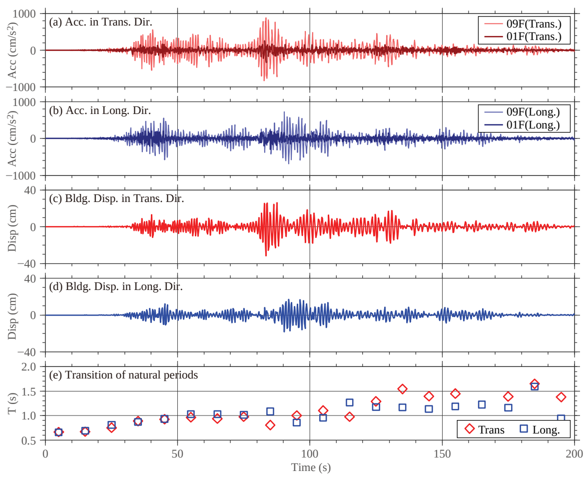


Fig. 1 Records of strong motion

Long-period earthquake ground motions in Osaka Bay

During the earthquake, long-period earthquake ground motions were observed in Tokyo, Osaka and other large cities. One example is the 55-story steel office building on the coast of Osaka Bay that is 770 km away from the hypocenter. Photo 2 and Fig. 2 show the appearance of the building and 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. The pseudo velocity response spectra for the 1st floor records (Fig. 3) show clear peak at about 7 second period resulted in large earthquake responses at the top due to a resonance phenomenon.

Photo 2 55-story steel office building (Osaka Bay)

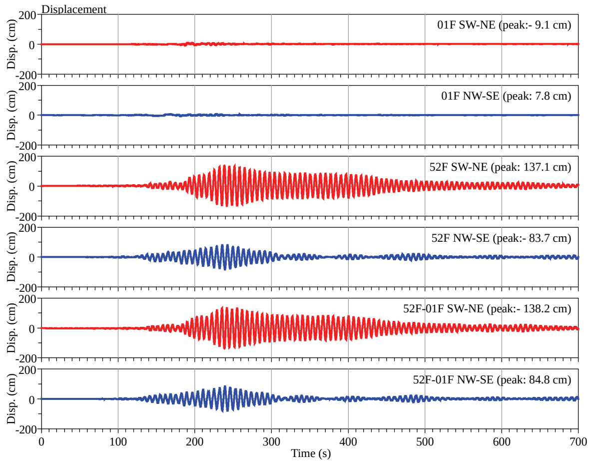


Fig. 2 Records of strong motion

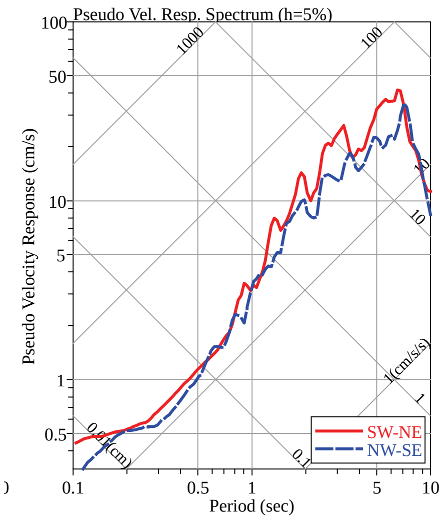


Fig. 3 Pseudo velocity response spectra with damping ratio of 5%

BUILDING AND RESIDENTIAL LAND DAMAGE BY EARTHQUAKE MOTION

The 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 Tonegawa River and the reclaimed ground on Tokyo

Bay, thus NILIM and BRI team selected the locations of the reconnaissance study as shown in Fig. 4 with the exception of the area near the Fukushima Daiichi Nuclear Power Station.

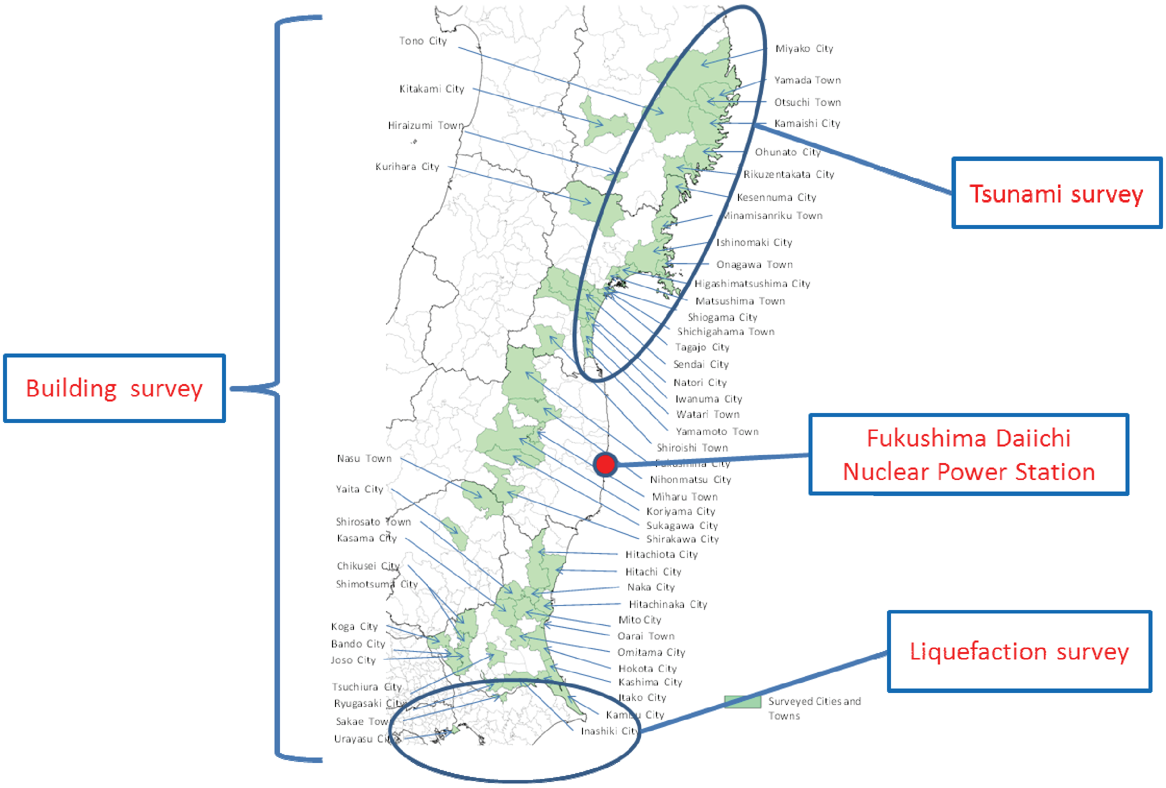


Fig. 4 Locations of field surveyed cities and towns

Building damage by earthquake motion

Wood houses

Most of the patterns of the damages to the wood houses by the earthquake were observed in past destructive earthquakes. They are the inclination and/or collapsed of the 1st story of wood houses with store as shown in Fig. 5 and Fig. 6 and the fallen down of the finishing due to structural bio-deterioration shown in Fig. 7. Collapse of the 2nd story shown in Fig. 8 was quite unusual.

Falling of roof tile is observed everywhere at the surveyed locations, but the damage in Fukushima and Ibaraki prefectures seemed more serious than that in Miyagi prefecture where large earthquakes struck frequently.

Fig. 5 Inclination of 1st story

Fig. 6 Collapse of 1st story

Fig. 7 Fallen down of finishing (bio-deterioration)   Fig. 8 Collapse of 2nd story

Steel buildings

Steel gymnasiums are surveyed extensively in Ibaraki prefecture, as the structural system of them is similar to that of factories and warehouses. Most of the patterns of the damages were observed in past earthquakes, which are the rupture of braces at the joint as shown in Fig. 9 and the rupture of roof braces in Fig. 10. The spalling of concrete at the joint of the steel roof structure and the reinforced concrete column as shown in Fig. 11 and the buckling of latticed column in Fig. 12 were also observed. The dropping of ceiling was observed at many gymnasiums (Fig. 13) which could not be used for emergency evacuation sites.

Fig. 9 Rupture of brace joint

Fig. 10 Rupture of roof braces

Fig. 11 Spalling of concrete at joint

Fig. 12 Buckling of latticed column

Fig. 13 Dropping of ceiling

Reinforced concrete buildings

Almost all of the damages of reinforced concrete buildings in the earthquake were observed in past destructive earthquakes. For example, they are the story collapse in the soft 1st story (Fig. 14) and/or mid-story (Fig. 15) of buildings due to shear failure of columns (Fig. 16), and so on. The nonstructural walls adjacent to the door of residential buildings suffered damage quite frequently as shown in Fig. 17. The retrofitted buildings behaved well in general with some exception as shown in Fig. 18.

Fig. 14 Collapse of soft 1st story

Fig. 15 Collapse of mid-story

Fig. 16 Shear failure of column

Fig. 17 Nonstructural wall failure

Fig. 18 Damage of retrofitting

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 them performed structurally very well (Fig. 19) which was also clarified by the recorded motions. The steel dampers absorbed earthquake energy by the plastic deformation (Fig. 20). However, the lead dampers suffered cracks due to many cycles of small amplitude of reversed deformation as shown in Fig. 21. Damage to the expansion joints (Fig. 22) was seen quite frequently which should be improved very soon.

Fig. 19 Seismically isolated building performed well

Fig. 20 Yielded steel damper

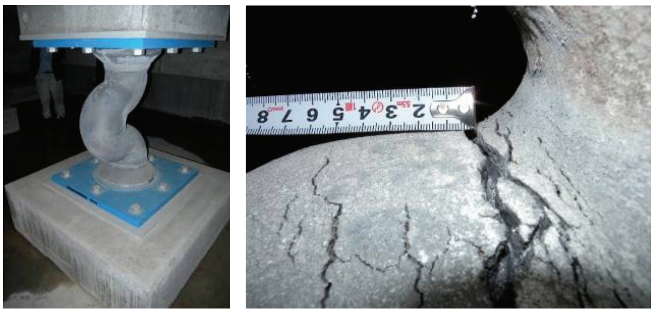


Fig. 21 Lead damper cracked

Fig. 22 Expansion joint deformation

Residential land
In the catchment area of Tonegawa 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 or fissures on the foundations investigated were not observed as shown in Fig. 23.

In Sendai city, the ground transformation by sliding of the housing site embankment was observed as shown in Fig. 24, just like the one under the 1978 Miyagi-Ken-Oki earthquake.


Fig. 23 Tilted house by liquefaction


Fig. 24 Ground transformation by sliding

Building damage by tsunami

The coastal area along Aomori prefecture to Miyagi prefecture shown in Fig. 4, 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 general reconnaissance 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.

Damage patterns
From the general survey on the reinforced concrete buildings, steel buildings and wood houses which suffered tsunami induced damage, the following damage patterns are obtained.

Movement or complete washed away was observed especially in wood houses and steel buildings as shown in Fig. 25. Overturning with the effect of buoyancy was observed mainly in reinforced concrete buildings and exceptionally in steel building as shown in Fig. 26. Tilting by scouring was seen as shown in Fig. 27. Story collapse, out-of-plane deformation of wall and washed out of claddings shown in Fig. 28 are due to horizontal force by tsunami. Figure 29 shows the effect of debris impact, and Fig. 30 shows several survived wood houses by the shading effect of the tsunami front building.



Fig. 25 Movement and complete washed away (left: wood house, right: steel building)

Fig. 26 Overturning
(left: reinforced concrete building, right: steel building)

Fig. 27 Tilting by scouring

Fig. 28 Story collapse of 1st story (left), out-of-plane wall deformation (middle) and washed out of claddings (right)

Fig. 29 Debris impact

Fig. 30 Shading effect by front building

STATE OF THE ON-GOING COPING ACTIVITIES

From the study and survey of the building damage and so on explained above, the following issues are obtained to be counter-measured administratively: establishing and/or modifying the related building technical standards.

- Effect of long-period earthquake ground motion on the buildings with long natural periods should be considered
- Fallen down of ceilings especially in gymnasium type of buildings should be counter-measured
- Subsidence and inclination of residential land of detached houses by liquefaction should be counter-measured
- Design guidelines for tsunami evacuation buildings against tsunami force should be established

Concrete research on each issue is explained as follows. The research results are planned to be implemented in the building technical standards by the administration taking into account the neutral expert opinions by the Building Structural Codes Committee (Fig. 31) established in NILIM.

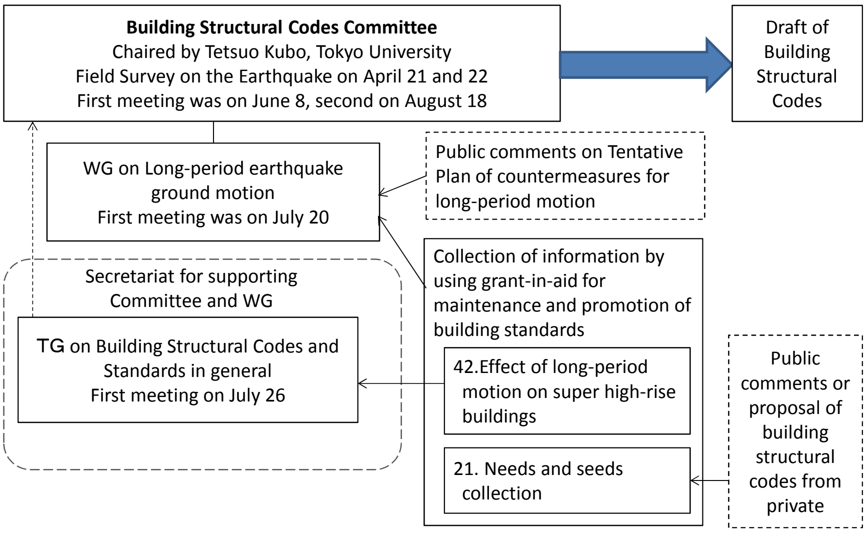


Fig. 31 Building Structural Codes Committee

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 is raised, and the prediction maps are announced based on detailed calculation (Headquarter for Earthquake Prediction 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 the occurrence of the earthquake and does not include the combined mega-earthquakes such as the Tonankai-Nankai earthquake for instance.

NILIM and BRI with the collaboration of the administration 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 and received several hundreds of public comments. From the earthquake, numbers of high quality record data base became available and additional validation studies on the empirical prediction method is now undergoing. Figure 32 shows the predicted motion for Nankai earthquake compared with other researches results.

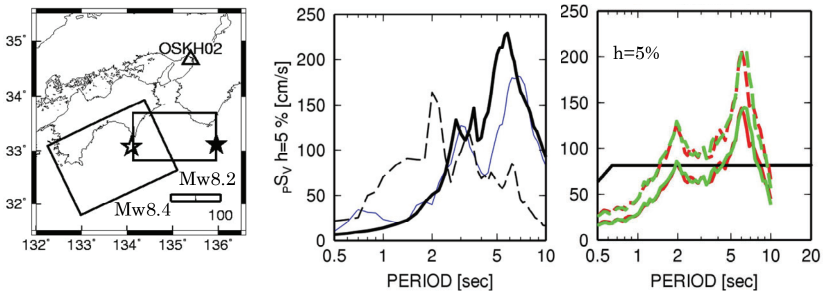


Fig. 32 Source model (left), predicted velocity response spectrum at Osaka by other researchers (middle), and prediction by our empirical prediction method (right) for Nankai earthquake

Fallen down of ceilings

The problem of fallen down of the ceilings which cover large space such as gymnasiums and so on has been indicated by NILIM and BRI since 2001 Geiyo earthquake, and technical advice to keep appropriate clearance between ceiling and surrounding structure and to install appropriate amount of diagonal braces on hanging bolts as shown in Fig. 33 with the collaboration of the administration.

In the earthquake, huge number of large space ceilings fell down and even casualties occurred. Therefore, extensive detailed survey on fallen down ceilings in the earthquake was initiated, where 151 damaged ceilings are collected and 11 of them were studied in detail. Based on this study with the previous knowledge, the current qualitative technical advice is under the study to be modified into much quantitative one.

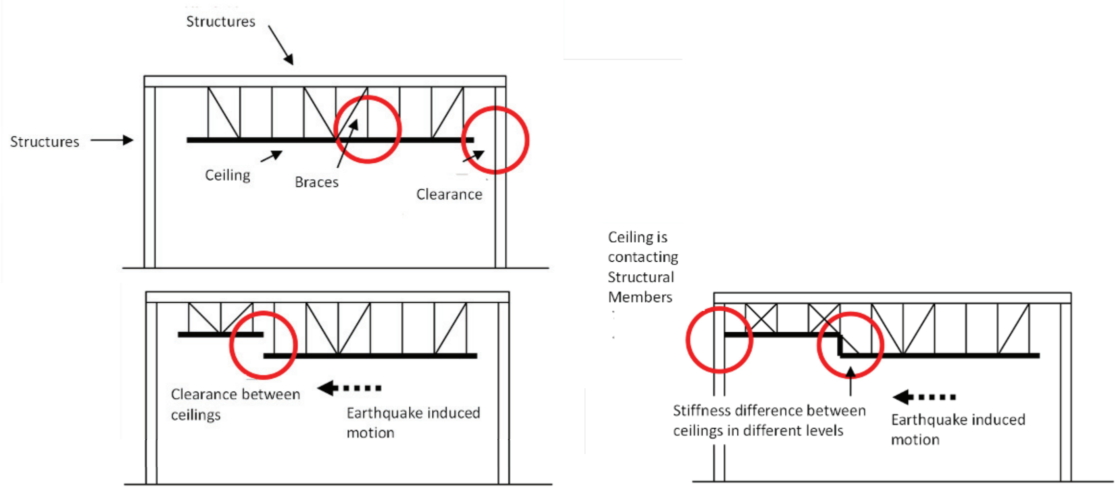


Fig. 33 Schematic explanation of current technical advice on details of ceilings

Liquefaction

For wood houses, the structural calculation is released in the Japanese Building Standard Law. Thus, the liquefaction countermeasures cannot be considered at present in the building construction for the detached houses. Vast liquefaction damage of residential land in the earthquake can be a reason of modification to more strict requirements in the law, but it may be an excessive requirement for the land of lower risk of liquefaction. Therefore, a study was started on the application of the system of performance indication to such detached houses answering to the social demand in the consumer protection on liquefaction of residential land.

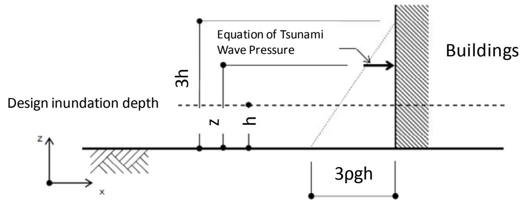
Considering the usable cost for the performance indication for residential houses, the Swedish weight sounding test method may be the available foundation investigation tool. Currently, possibility of the classification of the liquefaction risk mainly by the Swedish method together with public information such as micro ground configuration and ground water level and so on is studied.

Tsunami

As for the design of buildings against tsunami force, the guidelines for tsunami evacuation buildings (Cabinet Office 2005) are the unique technical information at present. 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 Fig. 34 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).

About 100 buildings were carefully selected and studied in detail as explained above. 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 35 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.

In the tentative guidelines announced from the administration 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 500 m or larger from the coastline and river in addition to shading effect. The effect of the openings of the building is also taking into account in the tentative guidelines.



Equation of Tsunami Wave Pressure: $q_x = \rho\, g\, (3h - z)$

q_x: design tsunami wave pressure (kN/m^2)
ρ: density of water (t/m^3)
g: gravitational acceleration (m/s^2)
h: design inundation depth (m)
z: height from the ground ($0 \leqq z \leqq 3h$) (m)

Fig. 34 Design tsunami force in the guidelines by the Cabinet Office

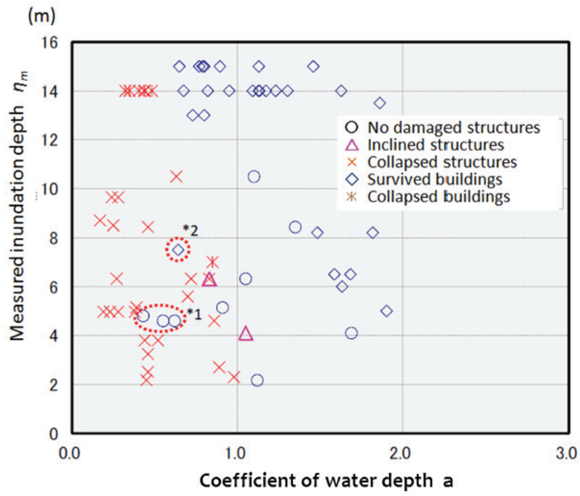


Fig. 35 Estimated coefficient of water depth of detailed studied buildings

CONCLUSIONS

The National Institute for Land & Infrastructure Management (NILIM) and the Building Research Institute (BRI) collaborated in the process of the recorded strong motions in and around instrumented buildings and also in the reconnaissance study of damaged buildings and residential land by the earthquake and the tsunami. In this paper, the outline of the collaborated work is presented first and then the state of the on-going coping activities on selected issues - long-period earthquake ground motion, fallen down of ceilings, liquefaction and tsunami - in order to establish necessary technical standards.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the members of NILIM and BRI who served for data analyses of observed strong motions and site 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.

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