Earthquake Engineering Research Framework toward CIB Research Roadmap Based on the Lesson Learnt from the Great East Japan Earthquake

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Research and Development Roadmap for Earthquake Engineering and Building

The Building Research Institute in Japan (so far referred to as the BRI) has conducted various activities such as research and development on housing, building and urban planning technology, and international training on seismology and earthquake engineering, systematically and continuously from the fair and neutral perspective of a public-sector research institute. In the spring of 2012, the CIB Regional Office of Japan was established by the BRI. The BRI will play a leadership role of CIB activities in Japan. Meanwhile, the Great East Japan Earthquake occurred on March 11, 2011 and caused tremendous damage to buildings and houses and enormous human losses by ground motion and tsunami. Based on lessons learnt from this earthquake disaster, the BRI has decided to develop a roadmap for earthquake engineering research and development for buildings. The roadmap will be utilized in the activities of the current working commission W114 (Earthquake Engineering and Buildings) in CIB. Firstly, this paper introduces the activities of the BRI after the Great East Japan Earthquake and summarizes the lessons from this tragedy. Then, the draft of Earthquake Engineering Research Framework toward CIB Research Roadmap for research and development for earthquake engineering is described. At the beginning of the proposed framework, the "Vision" describes the final objective of the roadmap. Then, "Mission" describes the research and development items to realize the vision. The "Goals and Objectives" follows describing more specific contents corresponding to each item of the Mission.

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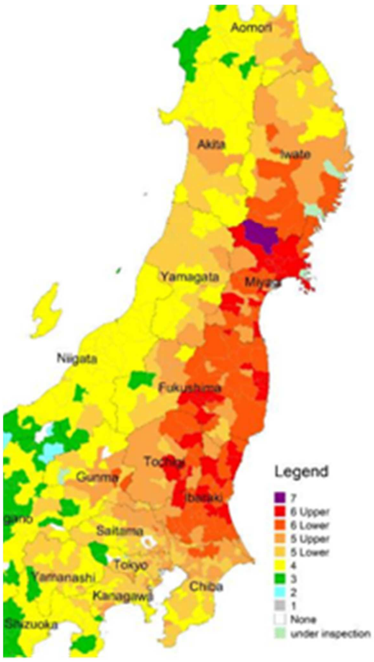
1. Introduction

This paper presents the earthquake engineering research framework toward CIB research roadmap based on the lessons learnt from the 2011 off the Pacific coast of Tohoku earthquake (the Great East Japan earthquake) (hereinafter referred to as the Tohoku earthquake). Firstly, this paper introduces the outline of the Tohoku earthquake, the strong motion observed mainly by the Building Research Institute (BRI) Strong Motion Network, the motion induced building damage and the tsunami induced building damage by the Tohoku earthquake. Joint activities to establish technical standards by the National Institute for Land & Infrastructure Management (NILIM) and BRI collaborated with the administration are also introduced briefly. Based on the experiences of damage survey for the Tohoku earthquake and BRI's research activities and CIB's secretary's helpful suggestions, the earthquake engineering research framework for research roadmap is described.

2. Lessons Learnt from the Great East Japan Earthquake

The Tohoku earthquake of moment magnitude (Mw) 9.0 occurred at 14:46 JST on March 11, 2011 and generated gigantic tsunami in the Tohoku and Kanto Areas of the north-eastern part of Japan. 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 according to U.S. Geological Survey [1]. An earthquake of Mw 7.5 foreshock preceded the main shock on March 9 and many large aftershocks followed including three Mw 7-class aftershocks on the same day of the main shock. As the epicentral distribution of the aftershocks of the Tohoku earthquake (hypocentral region) is widely located off the coast of the prefectures of Iwate, Miyagi, Fukushima and Ibaraki with approximately 450km in length in North-South direction and 150km in width in East-West direction. The distance from these prefectures to the fault plane is almost the same, thus the places with the seismic intensity of approximate 6 (6+ or 6-) according to the Japan Meteorological Agency (JMA) widely spread in these prefectures. The maximum JMA seismic intensity of 7 was recorded by the strong motion recording network (K-NET) [2] of the National Research Institute for Earth Science and Disaster Prevention (NIED) at Kurihara City (K-NET Tsukidate) shown by the purple color in Fig. 1.

Field survey by NILIM and BRI was started from Kurihara City and was followed by the locations shown in Fig. 2. In the coastal area from Aomori Prefecture to Miyagi Prefecture, the tsunami induced building damage was mainly surveyed. The area facing to the Pacific Ocean in Fukushima Prefecture was excluded from the survey in the cause of the accident in Fukushima Daiichi Nuclear Power Station. At the catchment basin area of Tone River in the border between Ibaraki and Chiba Prefectures and Urayasu City on the Tokyo Bay, damage of residential land associated with liquefaction was surveyed.



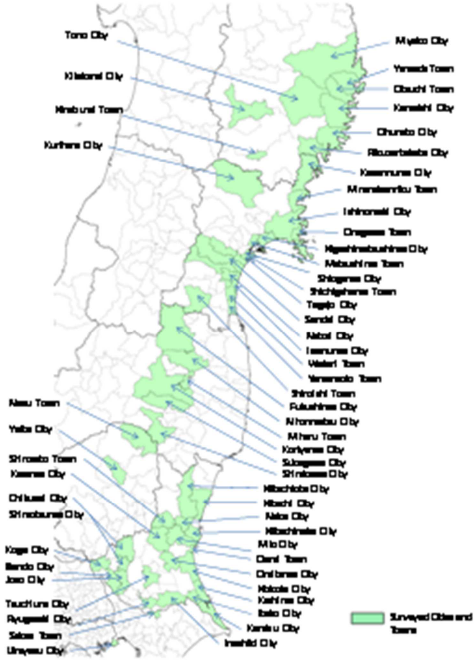


Figure 1: JMA Seismic Intensity Map ***Figure 2: Locations of Surveyed Areas***

2.1 Earthquake and Ground Motions

2.1.1 Characteristics of Earthquake Motions

During the Tohoku earthquake, severe ground motions were observed in wide area, and massive amounts of strong motion records were accumulated by K-NET of NIED [2]. From the acceleration records, a maximum acceleration in the N-S direction is understood to have reached almost 3700 cm/s^2, representing that the main shock caused excessively severe earthquake motions. A response in the N-S direction with a period of about 0.2 seconds becomes particularly large. This indicates earthquake ground motions that are dominated by short periods.

2.1.2 Results of BRI Strong Motion Network

The BRI conducts strong motion observation that covers buildings in major cities across Japan [3]. When the Tohoku earthquake occurred, 58 strong motion instruments placed in Hokkaido to Kansai Areas started up. Locations of the strong motion stations are plotted in Fig. 3 and Fig. 4. Among them, about 30 buildings suffered a shaking with seismic intensity 5- or more. This section presents some characteristic strong motion records.

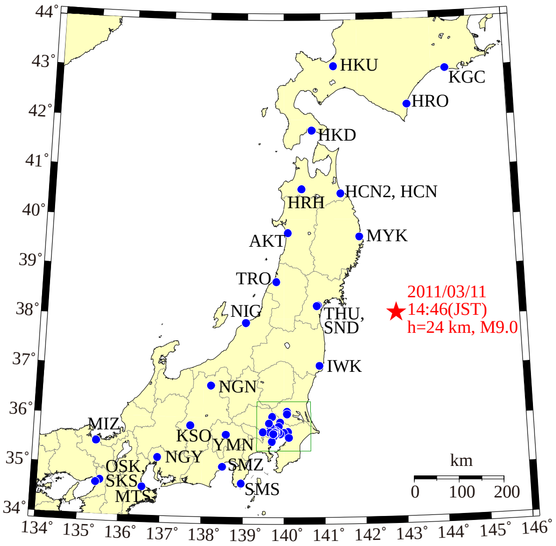


Figure 3: Locations of Epicenter (★) and Strong Motion Network (●)

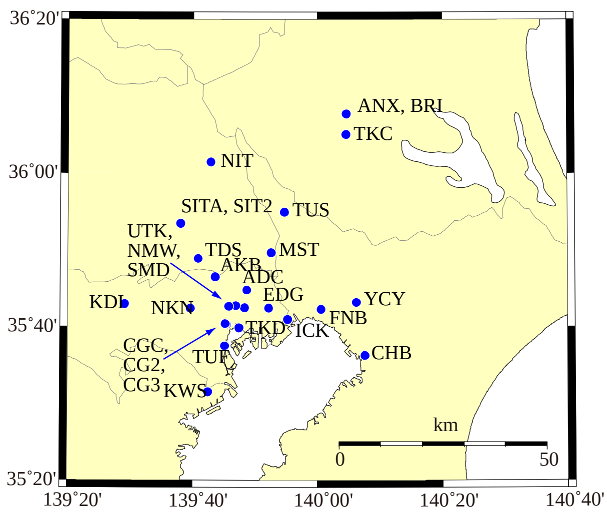


Figure 4: Strong Motion Network in Kanto Area (corresponds to green rectangle in Fig. 3)

Among buildings in the BRI Strong Motion Network, at least 4 buildings suffered severe earthquake motions and then some damage. One example of the damaged buildings is the building of the Tohoku University. This is the 9-story steel reinforced concrete (SRC) school building located in the Aobayama Campus. This building has a history of strong motion recordings. Strong motion records on the ninth floor of the building obtained in the 1978 Miyagi-Ken-Oki earthquake have represented a maximum acceleration of more than 1000 cm/s^2. During the Tohoku earthquake, multi-story shear walls suffered flexural failure and other damage. Thick and thin lines in Fig. 5 (a) and (b) represent acceleration waveforms on the first and the ninth floors, respectively. Maximum accelerations on the first floor exceeded 330 cm/s^2 in both of the directions. A maximum acceleration on the ninth floor was 2 to 3 times larger than on the first floor, and exceeded 900 cm/s^2 in the transverse direction. The fundamental natural periods in Fig. 5 (e) represented about 0.7 seconds at the initial stage of the earthquake motion in both of the directions, but increased to about 1 second in the first wave group at the time of 40 to 50 seconds, and increased from 1.2 seconds to about 1.5 seconds in the second wave group at the time of 80 to 100 seconds. Due to the seismic damage, the fundamental natural period finally became twice longer than that at the initial stage, and was reduced to 1/4 on a stiffness basis. In other case, long-period earthquake motions and responses of super high-rise buildings that are shaken under the motions have been socially concerned in recent years. When the Tohoku earthquake occurred, long-period earthquake motions were observed in Tokyo, Osaka and other large cities that are away from its hypocenter. This section presents two cases in Tokyo and Osaka from the BRI strong motion network. Fig. 6 shows strong motion records that were obtained from the 55-story steel office building on the coast of Osaka Bay that is 770 km away from the hypocenter. This figure shows absolute displacements in the SW-NE and in the NW-SE directions on the 1st floor, absolute displacements in both of the directions on the 52nd floor, and building displacements (relative displacements of 52th floor to 1st floor) in both of the directions, from the top to the bottom. A ground motion displacement was not large, or 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 coincidence of the fundamental natural period (6.5 to 7 seconds) in the steel office building with a predominant period of the earthquake motion is considered to have caused a resonance phenomenon and then large earthquake responses were observed at the top.

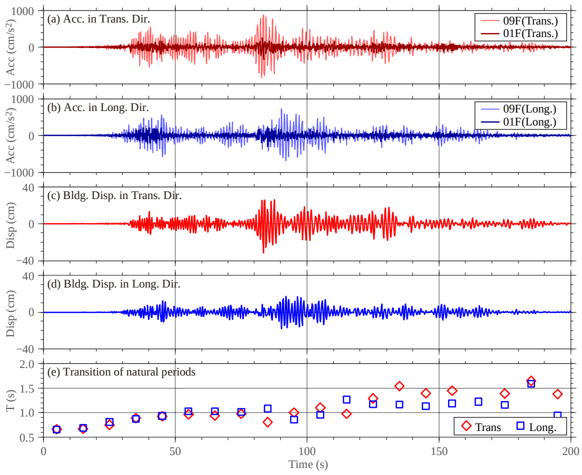


Figure 5: Strong Motion Records of the Tohoku University and Transition of Natural Periods

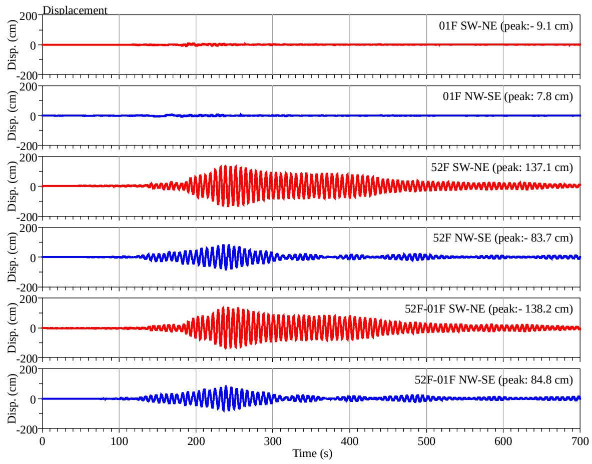


Figure 6: Displacement observed at a 55-story Office Building in Osaka Bay Area

2.2 Damage of Buildings due to Earthquake Motions

2.2.1 Damage of Wood Houses

As a result of damage survey on the wood houses due to ground motion in each city, the followings were provided.

1) The damage on the many wood houses due to ground motion was confirmed in Osaki City in Miyagi Prefecture, Sukagawa City in Fukushima Prefecture, Nasu Town in Tochigi Prefecture, and Hitachiota City and Naka City in Ibaraki Prefecture. 2) Though the seismic intensity 7 was recorded in Kurihara City, Miyagi Prefecture, the damage on wood houses were not so severe. 3) The damage on the wood houses caused by the failures of residential land was confirmed in Sendai City, Miyagi Prefecture, and Yaita City, Tochigi Prefecture. 4) The damage of the roof tile in Fukushima and Ibaraki Prefectures was much larger than Miyagi Prefecture where an earthquake occurred more frequently. 5) The possibility that the ground motion was amplified on the land filled up from meadow or rice field, even if the residential land did not fail, was suggested in Kurihara City, Osaki City in Miyagi Prefecture, Nasu Town in Tochigi Prefecture, Hitachiota City, Naka City, Joso City, Ryugasaki City in Ibaraki Prefecture, and so on. 6) In Osaki City, Miyagi Prefecture, the plural rare damage examples that residual story deformation of 2nd floor was larger than that of 1st floor were confirmed.

2.1.3 Damage of Reinforced Concrete Buildings

The types of the damage of RC and SRC buildings that were observed through the site investigation are classified into those for structural and non-structural elements in the following.

The damage of structural elements are; 1) Collapse of first story, 2) Mid-story collapse, 3) Shear failure of columns, 4) Flexural failure at the bottom of column and base of boundary columns on multi-story shear walls, 5) Pullout of anchor bolts and buckling of longitudinal reinforcements at exposed column base of steel reinforced concrete (SRC) buildings, 6) Shear failure or bond splitting failure of link beams of multi-story coupled shear walls, 7) Building tilting, 8) Destruction, failure or tilting of penthouses, 9) Damage of seismic retrofitted buildings. The damage of non-structural elements are; 1) Flexural failure at the bottom of column with wing wall, 2) Damage of non-structural wall in residential building, 3) Damage and falling of external finishing, 4) Tilting or dropout of components projecting above the roof, 5) Collapse of concrete block wall and stone masonry wall

2.1.4 Damage of Steel Gymnasiums

The damage of the gymnasiums was classified into the types of 1) to 7). The types of 1) to 6) and the type of 7) refer to structural damage and to non-structural one, respectively.

1) Buckling and fracture of brace member and fracture of its joint, 2) Buckling of diagonal member of latticed column, 3) Damage of connection (bearing support part) between RC column and steel roof frame, 4) Deflection, buckling and fracture of roof horizontal brace, 5) Cracking of column base concrete, 6) Other (Overturning of floor strut, etc.), 7) Non-structural damage such as dropping of ceilings and exterior walls and breakage of windows

2.1.5 Damage due to Failures of Residential Land

The outline of the damage situations in the investigate scope is as follows.

Regarding damage caused by liquefaction, extensive damage such as sand boiling or ground transformation associated with liquefaction was confirmed in the catchment area of Tone River and the coastal zone of Tokyo Bay. Highly tilted buildings were seen, but visual cracks or fissures on the foundations investigated were not observed. Regarding damage to housing area, large damage with transformations such as ground sliding was observed mainly in the elevated and developed housing area (particularly marginal part). In some areas, transformations occurred again in the developed lots that had been affected by the past earthquakes.

2.1.6 Response of Seismically Isolated Buildings

Investigation results of Seismically Isolated (SI) buildings in Miyagi Prefecture and one SI building in Yamagata Prefecture is summarized as follows;

1) Super-structures of SI buildings suffered almost no damage even under strong shaking with JMA intensity 6 upper. It verifies the excellent performance of SI buildings. 2) There are 8 buildings with scratch boards to measure displacement of the SI building floor. In most cases, the maximum displacement has been estimated as around 20 cm. There is one case with the maximum displacement estimated over 40 cm. 3) In some buildings, damage was observed at the expansion joints. It seems that parts of expansion joints were not well operated due to the large displacement of SI building floor during earthquake. 4) Subsidence of ground around the building was observed in some buildings. 5) Many cracks were found in lead dampers. These cracks might be increased by the aftershocks. 6) Peeling off of paint was observed widely for U-shape steel dampers. In some cases, residual deformation of steel was remained.

2.2 Damage to Buildings in Inundation Areas due to Tsunami

The purpose of this investigation is to understand an overview of buildings damaged by tsunami, to obtain basic data and information required to evaluate mechanisms for causing damage to the buildings and to contribute to tsunami load and tsunami-resistant designs for buildings such as tsunami evacuation buildings, by means of collecting building damage cases by tsunami, classifying the damage patterns for different structural categories, and making a comparison between the calculated tsunami force acting on buildings and the strength of the buildings. The NILIM and BRI jointly created a tsunami damage investigation team that consists of 27 members. The joint team collected national and international standards and codes concerning tsunami evacuation buildings and tsunami loads and surveyed about 100 buildings and structures in three site investigations.

The damage types of RC buildings observed through the site investigation are classified as followings; 1) Collapse of first floor, 2) Overturning, 3) Movement and washed away, 4) Tilting by scouring, 5) Fracture of wall (fracture of opening), 6) Debris impact. The damage types of steel buildings observed through the site investigation are classified as followings; 1) Movement and washed away by fracture of exposed column base, 2) Movement and washed away by fracture of capital connection, 3) Overturning, 4) Collapse, 5) Large residual deformation, 6) Full fracture and washed away of cladding and internal finishing materials. As for wood houses, in the case of a maximum inundation depth of about 1 m, most of houses could be remained. Some wood houses were damaged considerably due to debris impact. In the case of a maximum inundation depth of about 1 to 6 m, some wood houses where located behind the relatively substantial building for tsunami load such as a reinforced concrete building remained. In addition to that case, a tsunami load was reduced possibly due to many openings in the direction affected by tsunami, or a wooden house remained despite washed away of columns and external walls at the corner of the building. Several houses which have a reinforced concrete storey on the first floor, or a mixture of wooden and reinforced concrete structures, remained.

2.3 Joint Activities by BRI and NILIM

For political response based on the lessons, the following studies should be especially resolved by means of technical investigations. 1) Study on the design of tsunami evacuation buildings, i.e. Estimation of tsunami load, 2) Study on advanced seismic resistant design of suspension ceiling system, 3) Study on verification of seismic safety performance for super high-rise buildings and seismically isolated buildings under long-period earthquakes, 4) Study on information indication of liquefaction for residential houses

NILIM has been developing the draft of technical standards for the resolution. As for the research and development for the resolution, the research organizations designated by the Building Standard Development Promotion Program [4] of Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and BRI have been implementing as joint research. Thus, BRI has been playing the role for establishment on a domestic structural code with NILIM in Japan.

3. Earthquake Engineering Research Framework toward CIB Research Roadmap

The structure for CIB roadmap is shown in Fig.7. “Conceptual Framework” in Fig.7 could be common interest among each institute and organization and the other items in Fig.7 depends a great deal on the specific interests and situations of each institute and organization. Once “Conceptual Framework” will be determined, the other items could be discussed among each institute and organization. Thus, first of all, the comprehensive and strategic research framework should be shown. Based on the lessons learnt from the Tohoku earthquake, this paper presents the earthquake engineering research framework corresponding to “Conceptual Framework” in Fig.7 toward CIB research roadmap with reference to other materials [5,6]. The outline of framework is shown in Fig.8. The framework is triangle shape and consists of the following items; 1) Vision, 2) Missions, 3) Goals and Objectives. Based on the proposed framework, research agenda for BRI is finally shown as an example in the paper to show the relationships between the framework and specific research agendas.

3.1 Vision

Based on the experiences of The Tohoku earthquake, we recognized the importance of not only seismic safety performance of buildings but also post-earthquake continuous functionality against severe earthquake. Thus, the Vision which earthquake engineering research can contribute is “Safe and Secure Society” and “Resilient Society for Minimizing Disaster Loss”. Especially countries where frequent earthquakes occur like Japan should prepare the appropriate actions against before and after earthquake for realization of above mentioned society.

3.2 Missions

The Missions to achieve the vision are shown as follows, M1）Research for Earthquake Disaster Loss Mitigation, M2）Development of Technologies and Tools for Earthquake Disaster Loss Mitigation, M3）Dissemination and Promotion for Earthquake Disaster Loss Mitigation Measures, M4）Global Multidisciplinary Partnerships for Earthquake Disaster

Loss Mitigation, M5) Upgrading and Utilization of Required Resources for Earthquake Disaster Loss Mitigation.

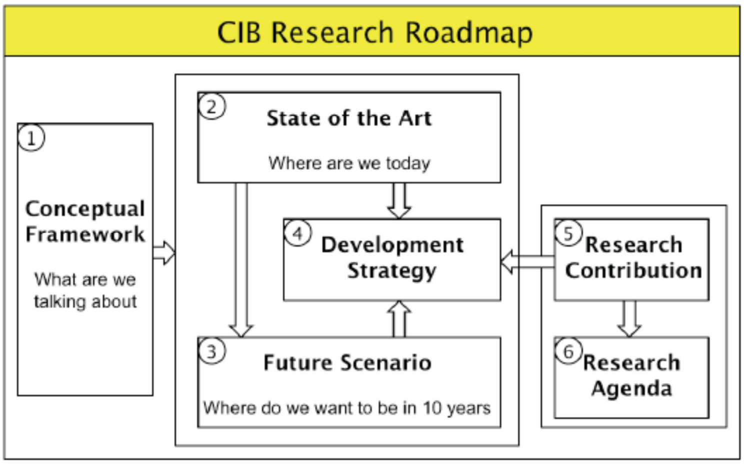


Figure 7: Structure for CIB Research Roadmap

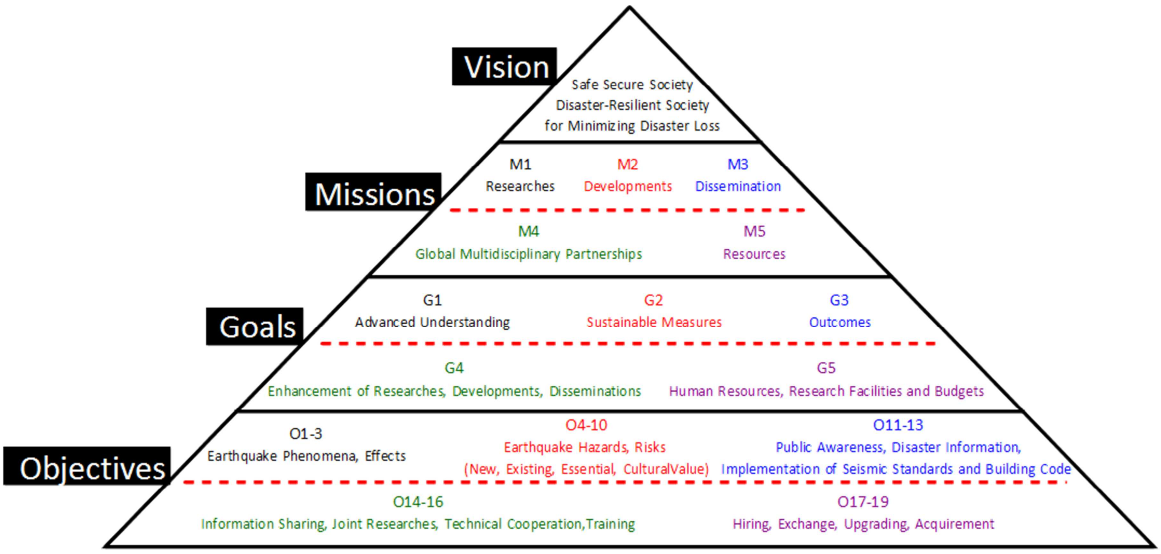


Figure 8: Structure of Earthquake Engineering Research Framework

3.3 Goals and Objectives

The Goals to achieve the Missions are shown as follows, G1) Advanced Understanding of Earthquake Phenomena and Impact, G2) Development of Sustainable Measures to Mitigate Earthquake Disaster Loss and Impact on Individuals, the Built Environment, and Society-at-Large, G3) Dissemination and Promotion of Earthquake Disaster Loss Mitigation Measures for Earthquake Professionals, Owners, Users, G4) Enhancement of Researches, Developments, Disseminations for Earthquake Disaster Loss Mitigation Based on Global Multidisciplinary Partnerships, G5) Acquirement and Upgrading, Utilization of Required Human Resources, Research Facilities and Budgets for Earthquake Disaster Loss Mitigation.

Those Goals are long-term targets to support the Missions and associated with the Objectives. The relationship between Goals and Objectives is shown in Fig. 3.3. G1, 2, 3, corresponding to M1, 2, 3 respectively are closely linked and G3 is generally disseminations and promotions with the outcome of G1 and G2. G4 corresponding to M4 is the important item to enhance G1, 2, 3 globally. G5 corresponding to M5 is the basis of activities for other Goals. Each Objective is related to the Goals and set to achieve the Goals.

The Objectives relevant to G1 are follows, O1) Advanced Understanding of Earthquake Generation, Propagation and Relevant Phenomena, O2) Advanced Understanding of Earthquake Effect on Structures and the Surrounding Built Environment, O3) Advanced Understanding of Earthquake Effect on the Societal Activities. For better understanding, each example on O1 to O3 is mentioned as followings, O1) Fault model evaluation, Earthquake propagation evaluation, Near fault evaluation, Tsunami force evaluation, O2)

Effective Input motion evaluation based on strong motion records, sophisticated method on strong motion observation for structures, Response evaluation for structures, Liquefaction evaluation, O3) Post-Earthquake damage information, Post-Earthquake scenarios.

The Objectives relevant to Goal2 are follows, O4) Development of Technologies and Tools to Assess Earthquake Hazard, O5) Development of Technologies and Tools to Assess Earthquake Risk Scenarios, O6) Development of Technologies and Tools to achieve Seismic Safety Performance of New Structures, O7) Development of Technologies and Tools to Improve Seismic Safety Performance of Existing Structures, O8) Development of Technologies and Tools to Enhance Seismic Resiliency of Essential Structures in Large Urban Areas, O9) Development of Technologies and Tools to continue Post-Earthquake Serviceability of Structures with Cultural Value, O10) Development of Seismic Standards and Building Codes Corresponding to Social Needs. For better understanding, each example on O4 to O10 is mentioned as followings, O4) Updating of existing hazard map, Technical standards of earthquake load, Earthquake evaluation techniques corresponding to construction sites, O5) Earthquake loss and risk evaluation, Performance evaluation and indication tool including excessive load, Risk communication tool, Rapid and detailed assessment techniques for damaged structures, Damage evaluation techniques for structures based on strong motion records, O6) Seismic safety performance evaluation techniques for new structures, New materials, technologies and structural systems, O7) Seismic safety performance evaluation techniques for existing structures, Seismic retrofit technologies, O8) Earthquake damage evaluation techniques and damage mitigation measures, Post-earthquake functionality evaluation techniques for essential structures, O9) Seismic damage evaluation techniques and mitigation measures for structures with cultural value, Serviceability performance evaluation techniques for structures with cultural value, O10) Structural design guidelines for tsunami evacuation buildings, Standards related to long-period component of ground motion and base-isolation/seismic control.

The Objectives relevant to Goal3 are follows, O11) Technical Supports for Implementation of Seismic Standards and Building Code Corresponding to Social Needs, O12) Information on serviceability of Structures after Strong Motion, O13) Support for Public Awareness on Comprehensive Earthquake Hazards and Risks. For better understanding, each example on

O11 to O13 is mentioned as followings, O11) Educational activities (seminars, lectures) to contribute smooth implementation of current structural relevant codes for structural engineers, O12) Rapid earthquake announcement, Offer of information on continuous use of structures using strong motion record network, O13) Support of activities to enhance the public awareness and preparedness of earthquake hazards and risks mitigation, Support for making guidebooks on earthquake risk mitigation measures, Support of earth-sciences and earthquake-engineering education, Application of earthquake risks evaluation methods in each region, Application of performance indication methods considering serviceability of structures after earthquake.

The Objectives relevant to Goal4 are follows, O14) Implementation of Information Sharing, Joint Researches and Surveys for Earthquake Disaster Loss Mitigation, O15) Technical Cooperation to Enhance Earthquake Disaster Loss Mitigation in Developing Countries, O16) Trainings for Earthquake Engineering Professionals. For better understanding, each example on O14 to O16 is mentioned as followings, O14) Sharing information with CIB and other international institutes, Joint survey with international institutes, Promotion of International joint research, O15) Cooperation to project on technical support for developing countries, O16) Training courses for knowledgeable specialists on earthquake hazards and risks in developing countries.

The Objectives relevant to Goal5 are follows, O17) Hiring and Utilization, Exchange of Researchers with High Level of Expertise, O18) Upgrading and Utilization of Advanced Research Facilities, O19) Acquirement and Priority Allocation of Research Budgets. For better understanding, each example on O17 to O19 is mentioned as followings, O17) Establishment of system for human resources required in each institute, Sharing information and joint research with visiting scholars, O18) Upgrading and utilization of facilities for experimental tests using scale-merit of laboratories and hybrid tests using IT technologies, O19) External research funds and the prioritized allocation for earthquake damage mitigation.

3.4 Investigation on validity of the Framework using BRI's research agendas

In order to investigate validity of the framework by showing the relationships between the research framework proposed and specific research agenda, BRI's research agendas will be introduced as an example in this section. BRI has specific research agendas in the medium-term plan based on the medium-term goal under the direction of the Minister, and has been promoting research and development efficiently. The specific research agendas are related to "Objectives" in the framework. BRI has two research agendas, one is priority research agenda which are socially significant and urgent, and the other is basic research agenda which are academically fundamental and leading. Regarding the earthquake engineering, BRI has 2 priority research agendas and 10 basic research agendas. The priority research agendas are "Study on explicit criteria for proper engineering judgement required in structural calculation" and "Study on advanced response evaluation technique for high-rise building structures under long-period earthquake." The former agenda is related to Objectives 6, 10. The latter agenda is related to Objectives 8, 10 and is also an issue to be countermeasured as a lesson of the Tohoku Earthquake. On the other hand, the typical basic research agendas are “Study on advanced mitigation techniques against earthquake and Tsunami in developing countries and training courses with latest, useful contents” and “Strong motion observation for buildings and the technology for application”. The former agenda is related to Objectives 15, 16. The latter agenda is related to Objectives 2, 12 and is also an issue to be solved as a lesson of the Tohoku Earthquake. Through above investigation, it is shown that the framework has an appropriate function to relate to specific research agenda using BRI’s current research agendas. We hope that the framework will be improved furthermore in W114 (Earthquake Engineering and Buildings) of CIB and be utilized among the relevant CIB members as the CIB Research Roadmap on earthquake engineering.

4. Conclusions

This paper described the earthquake engineering research framework toward CIB research roadmap based on the lessons learnt from the Great East Japan Earthquake and current BRI’s research activities. This framework consists of Vision, 5 Missions, 5 Goals and 19 Objectives and specific research agendas are related to Objectives and it is shown that the framework has an appropriate function to relate to specific research agenda using BRI’s current research agendas. It is expected that this framework will provide the basis of a framework for CIB Research Roadmap on earthquake engineering and be discussed among the related institutes and organizations.

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