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Lessons from the 2011 Great East Japan Earthquake Focused on Building Damage

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Abstract

A huge earthquake with the magnitude of 9.0 occurred in the Pacific Ocean off the coast of Tohoku district, Japan on March 11, 2011 (indicated as “the 2011 Great East Japan earthquake” hereafter) and caused huge physical damage and loss of life. The magnitude of this earthquake is the largest recorded in Japan since modern seismograms became available. The huge earthquake caused not only tremendous tsunami damage but also structural damage due to the severe ground motions with a long duration.

This paper describes the lessons from the 2011 Great East Japan earthquake, focused on the building damage, in relation to the observed ground motion characteristics from the engineering view points for countermeasures against the expected earthquakes in other area of Japan and also in foreign countries.

First, the following observed ground motion characteristics are addressed.

1) The observed high acceleration record at a K-NET site (MYG004) with maximum acceleration of 2,700 cm/s2 comprising high frequency content is investigated. It is found that the ground motion has no power to collapse houses and also topple the unfixed book.

2) Impact of long-duration motions focused on the cumulative responses of base-isolated buildings using K-NET (MYG006) data for not only main shock but also aftershocks and past earthquakes. It is found that cumulative response due to many past earthquakes is larger than that of main shock of the huge earthquake. Difference of the cumulative response due to geological structure in Kanto Basin is quantitatively investigated.

3) Site dependent ground characteristics with 3 times the difference in PGAs and PGVs based on observation data in Sendai City. Soil amplification should be enforced in seismic design possibly including seismic micro-zoning.

Then, the following specific features of building damage including housing land damage are addressed.

1) Damage features of the retrofitted 9-story SRC building at Aobayama campus of Tohoku University is investigated. Ground motion amplification in the hilly zone and the induced resonance phenomena is strongly related to the severe damage considering the non-stationary nature of ground motion and the nonlinearity of the building.

2) Foundation damage of the two pile foundation buildings damaged during the 1978 Miyagi-ken Oki earthquake is described together with other damaged pile foundation buildings. The two buildings were divided, black and white, during the 2011 Great East Japan earthquake due to after treatments of the 1978 earthquake. Balance of foundation and the superstructure is needed for the synthetic seismic performance of the whole building to be achieved.

3) Non-structural element and equipment damage are described. Ceiling board damage occurred at many multi-purpose halls, local governments’ halls and shopping centers, which caused human damage. It is needed to establish total balance of the structural elements, the non-structural elements, and the equipment.

4) The huge number of housing land damaged in Sendai City is described. The damage is caused by the valley-filled land with high water level and the ground motions with long-duration.

Finally concluding remarks are described including above findings.

Keywords: 2011 Great East Japan earthquake; building damage; ground motion characteristics; cumulative response

1. Introduction

A huge earthquake occurred in the Pacific Ocean off the coast of Miyagi, Japan on March 11, 2011 and caused massive physical damage and loss of life. The moment magnitude (Mw) of this earthquake, was 9.0, the largest recorded in Japan since modern seismograms became available. The fault plane has dimensions of 450km by 200km. The earthquake was followed by many aftershocks and also induced some other earthquakes. The huge earthquake caused not only tremendous tsunami damage but also structural damage due to the severe ground motion which continued for such a long duration. This earthquake has been named the 2011 off the Pacific coast of Tohoku Earthquake (indicated as "the 2011 Great East Japan earthquake" hereafter). The 2011 Tohoku Earthquake took the lives of about 18,000 persons mainly by tsunami, which closed up the evacuation problem. But, the status of vibration damage and lessons from the huge earthquake should be importantly informed for countermeasures of urban and buildings against the earthquakes in the future.

On March 11, 2011, the author experienced the severe shaking at 11th floor of a 13-story building (seismically controlled building with oil damper braces) at Aobayama campus of Tohoku University in Sendai, Japan. The very next day, the author started to quickly conduct a damage survey and investigated the ground motion characteristic and building damage, contributed to publish the damage survey reports by AIJ [1] and summarized the lessons of the Tohoku earthquake focused on ground motion characteristics and building damage [2]. The author also contributed to the development and utilization of Earthquake Early Warning (EEW) system. The status of the EEW utilization during the Great East Japan earthquake was reported together with the raised problems [3]. The author also has contributed to the recovery and reconstruction activities of local governments.

In this paper, lessons from the 2011 Great East Japan earthquake, focused on the building damage in relation to the observed ground motion characteristics, are described from the engineering view points of the countermeasures against the expected earthquakes in other area of Japan and other countries all over the worlds. First, the observed ground motion characteristics are described regarding the observed high acceleration record, the impact of long-duration motions, and site dependent ground motions. Then, specific features of building damage are described for the damage of the retrofitted building. Foundation damage and non-structural element damage are discussed together with housing land damage from the point view of total balance of seismic performance of the whole building.

2. Observed Ground Motion Characteristics

2.1 Feature of Huge Earthquake from the Point of Ground Motion

The 2011 Great East Japan earthquake is the first M9-class earthquake where many observation records were obtained. For this huge earthquake, various definition magnitude were determined; Surface magnitude Ms=8.1, Body wave magnitude m_B=7.3, and Local magnitude M_L=6.8, which shows that ground motion level has limitation. But it is noted that the huge earthquake comprises a series of large earthquakes with magnitude of 7- to 8-class.

Fig.1 shows locations of the five asperities generating earthquake waves together with the corresponding magnitude. The author has used the word, 'An attack in waves' in the explanation of building damage due to the huge earthquake. Buildings damaged by the first waves are attacked by the next waves. It is noted that the 1st and 2nd asperities, M7.7 and M8.0 are located off the Miyagi prefecture and the remaining three asperities, M7.2, M7.3, and M7.5, are off Fukushima prefecture.

Fig.2 shows the waveforms with different phase characteristics of observed strong motions at K-NET sites [5]. In the Miyagi prefecture, the observed ground motions (red color) show two distinctive phases, which are due to the first M7.7 and the 2nd M8.0 asperities. It is noted that the first phase ground motion is gradually increased due to slow velocity slip, which allowed people to evacuate. But the second phase ground motion suddenly increased pulse-like ground motion.

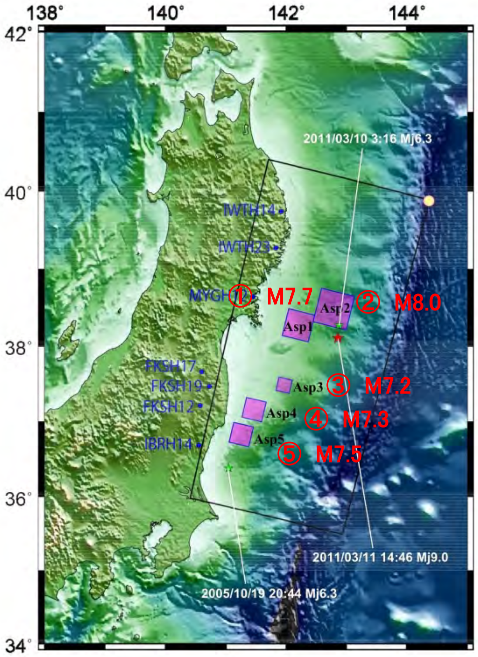
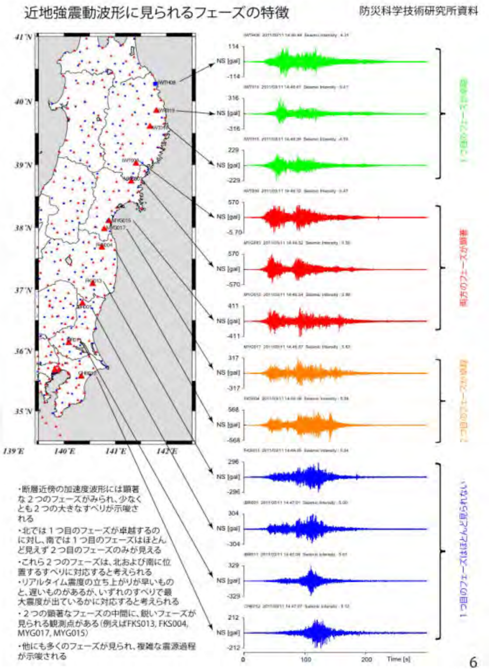


Fig.1 – Asperity location determined from KiK-net data by Kamae and Kawabe [4]



・断層近傍の加速度波形には顕著な２つのフェーズがみられ、少なくとも２つの大きなすべりが示唆される
・北では１つ目のフェーズが卓越するのに対し、南では１つ目のフェーズはほとんど見えず２つ目のフェーズのみが見える
・これら２つのフェーズは、北および南に位置するすべりに対応すると考えられる
・リアルタイム震度の立ち上がりが早いものと、遅いものがあるが、いずれのすべりで最大震度が出ているかに対応すると考えられる
・２つの顕著なフェーズの中間に、鋭いフェーズが見られる観測点がある（例えばFKS013, FKS004, MYG017, MYG015）
・他にも多くのフェーズが見られ、複雑な震源過程が示唆される

Fig.2 – Waveforms with diffrent phase characteristics of observed strong motions at K-NET sites [5]

2.2 Observed High Acceleration Records and Building Damage

In discussing the relation between ground motion and damage, it is necessary to investigate what kind of damage is caused by what kind of ground motion characteristics. This view point is important and walking alone of the seismic intensity is dangerous. It is necessary to distinguish the acceleration sensitive damage and drift sensitive damage.

Fig.3 shows the observed acceleration waveforms of the 3 components at K-NET Tsukidate (MYG004) during the March 11, Tohoku earthquake. The horizontal PGA in the NS component is 2,700 gal and in the EW component is 1,269. The high acceleration record was reported as, 'JMA intensity of VII, no victim' and a house adjacent to the site was not damaged as shown in Photo 1.

Fig. 4 shows 5%-damped pseudo velocity response spectra for the major stations, together with spectra of Takatori record at the 1/17/1995 Kobe earthquake and Kawaguchi-machi record at the 10/23/2004 Mid Niigata Prefecture earthquake as representatives of the earthquake records in the heavily damaged zone by the past disastrous earthquakes. Spectra of Takatori and Kawaguchi-machi records are predominant around 1-2 seconds, while spectrum amplitude at MYG004 (Terrace) is large at the shorter periods but the 1-2s amplitude is smaller. On the other hand, MYG006 (Osaki plain) and MYG013 (Sendai plain) have larger 1-2s amplitude compared to MYG004, and 4B9 at the center of Furukawa (Osaki plain) have similar amplitude level to that of Takatori.

As an investigation of this high acceleration record, the author performed a questionnaire investigation on real status of ground shaking [6]. It was determined that the questionnaire seismic intensity is one level smaller than the measured JMA seismic intensity. The problem of seismometer was also indicated [7]. It should be mentioned that the 3D shaking of JMA seismic intensity VII could not topple down a bookshelf without being fixed through the 3D-shaking table test of prototype room model with a manikin and furniture (ref. to Photo 2). The author cannot help identifying the problem of seismic intensity. It is important to clarify what kind of damage is caused by what kind of ground motion characteristics.

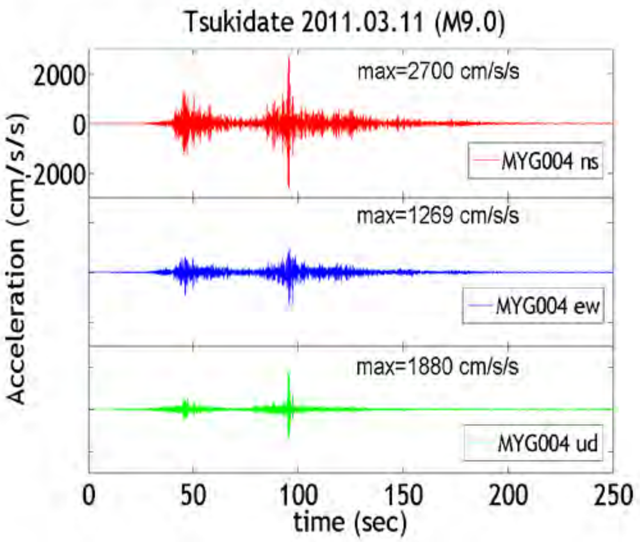


Fig.3 -Strong motion records at K-NET Tsukidate station during the 2011 Tohoku earthquake

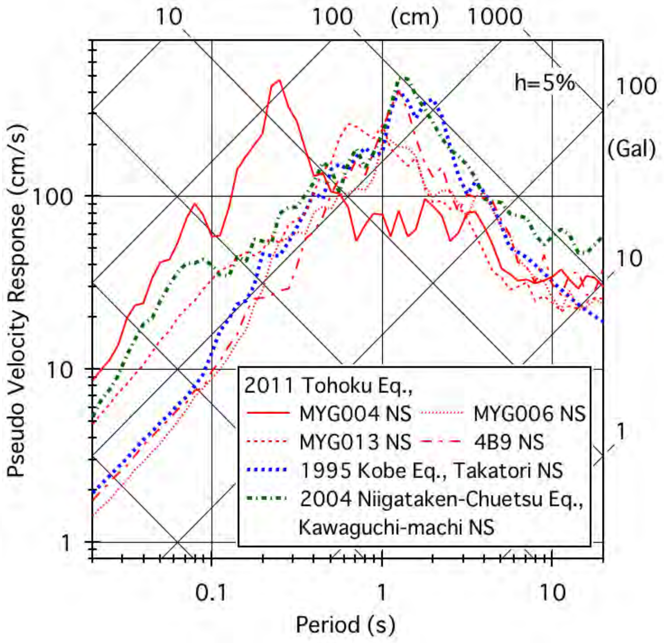


Fig.4 -Pseudo velocity spectra at observation stations with larger seismic intensity in Tohoku earthquake and past damaged earthquakes

Photo 1 – Features of a house adjcent to MYG004 site

Photo 2 – 3D-shaking table test for a proto-type room model

2.3 Long-duration Ground Motion and Cumulative Structural Response

The long-duration ground motions and consequently many numbers of displacement cycles due to a huge earthquake effect on cumulative structural response. It is important to investigate the relation between the structural damage and the cumulative displacement, and the cumulative energy. Consideration of effects due to many aftershocks followed by main shock is also important from the points of residue capacity of building structures, seismic diagnosis and emergency inspection.

It is reported that some lead damper type base-isolation devices were damaged, although base-isolated buildings generally worked well during the huge earthquake. A representative example is a base-isolated building in Osaki City, which site is located in sedimentary basin and suffered from long-duration ground motion during the Tohoku earthquake. To discuss this damage, the cumulative effects due to past earthquakes like the 2008 Iwate-Miyagi Nairiku earthquake including its aftershocks are investigated and found that these are significant as the main shock of the 2011 Great East Japan earthquake [8]. It is noted that the 4 second period content is dominant due to the deep underground structure of Osaki basin.

The specification of the investigated three types of lead rubber bearing isolation devices (LI11, LI12, LI13) with bi-linear dynamic hysteresis (Fig.5) is shown in Table 1. The allowable deformation is designed as 53 cm and limitation deformation is 70 cm. The equivalent periods of a base isolated building using the LI11, L12 and LI13 is assumed to be 4.36 s, 4.08 s, and 3.96 s, respectively.

Fig.6 shows cumulative displacement of lead rubber bearing isolators due to 220 observation records with larger PGA value of 10 cm/s^2 at MYG006 from 2000 to 2012. This figure shows that the cumulative displacements before the 3/11 main shock are larger than those during the March 11 main shock, and that very large cumulative displacement are given by the 4/07 after shock.

Fig.7 shows dynamic hysteresis response of the three cases of lead rubber bearing isolato. It is found that themaxium displacement is about 70 cm for LI12, which is about 20 cm lager than the cases of LI11 and LI13.

Table 1 – Specification of lead rubber bearing isolators

Device	D[mm]	Dp[mm]	k_1[kN/m]	Qy[kN]	δy[m]
LI11	1100	200	1990	271	0.136
LI12	1200	210	2200	299	0.136
LI13	1300	220	2360	328	0.139

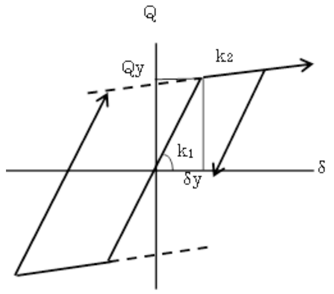


Fig.5 – Bi-linear histeresis model

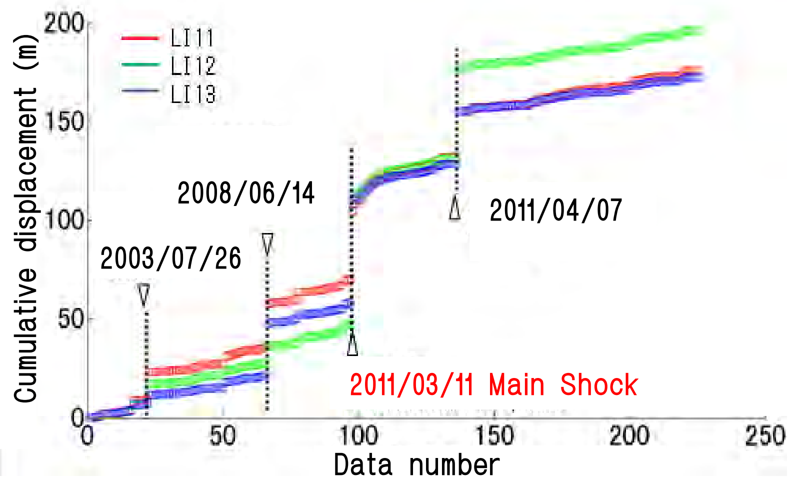


Fig.6 – Cumulative displacement of lead rubber bearing isolators due to 220 observation records at MYG006 with larger PGA value of 10 cm/s^2

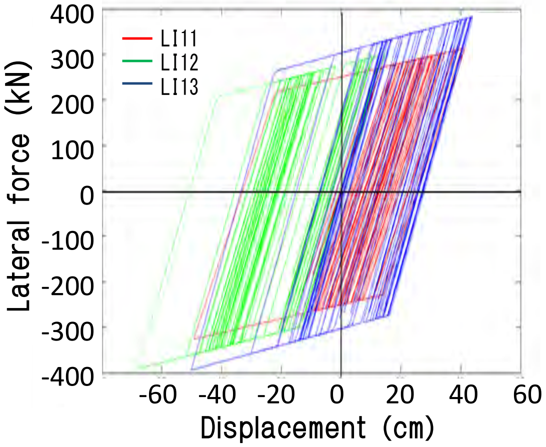


Fig.7 – Dynamic hysteresis response of lead rubber bearing isolators for ground motion at MYG006 due to March 11 main

It is important to recognize that long-period ground motions were amplified in the sedimentary basin like Kanto basin and Osaka basin where sky scrapers were shaken more than 10 minutes during the huge earthquake. The authors have investigated the cumulative responses' difference of long-period ground motions at the five K-NET sites in Kanto basin considering surface wave velocity distribution based on the deep underground structure [9].

Fig.8 shows cumulative energy expressed as equivalent velocity due to March 11 main shock at different K-NET sites as shown in Fig.9 in and around Kanto basin. It is recognized that the cumulative energy becomes lager in order of Kamogawa (CHB020), Hachioji (TKY004), Shinjyuku (TKY007), Makuhari (CHB008) and

Inage (CHB024) toward basin bottom. It is noted that long-period ground motion is composed of surface wave and its propagation is not simple attenuation but seems to follow ‘Earthquake motion propagation path’ toward the basin bottom.

In the sedimentary basin, the ground motion amplification should be taken into account for not only amplitude but also duration of ground motions.

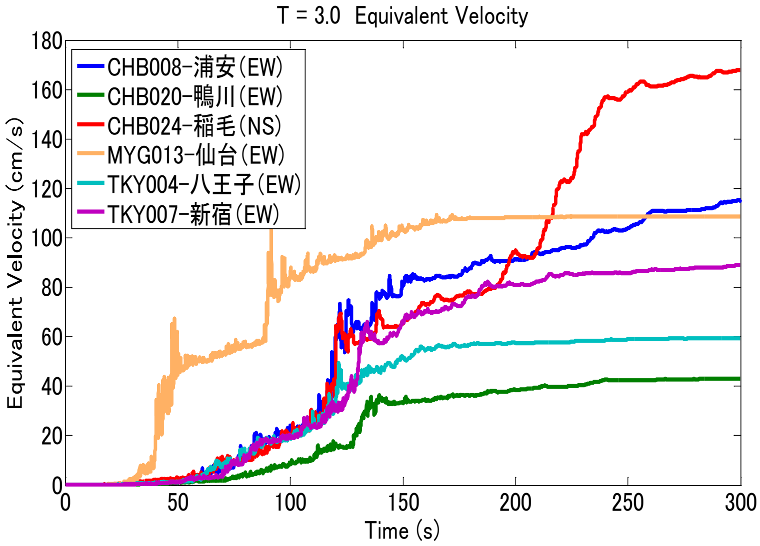


Fig.8 – Cumulative energy expressed as equivalent velocity due to March 11 main shock at different K-NET sites of Kanto basin

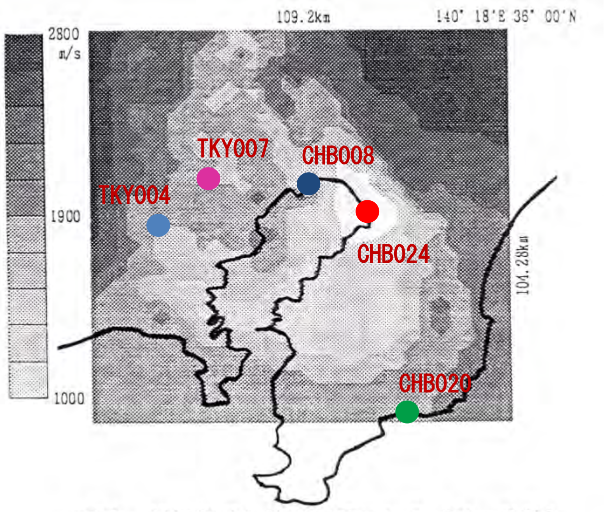


Fig.9 – Location of investigated K-NET sites on the velocity structure of Kanto basin (Motosaka et al., 1992) [10]

2.4 Different Ground Shaking due to Soil Conditions

It is recognized that urban area and buildings are on geological structures, a ‘Big Structure’, and the author realized necessity of appropriate seismic micro-zoning and law enforcement regarding ground motion amplification. Especially it is necessary to promote the consideration of building damage structure due to resonance to dominant frequency of the site. Namely seismic design considering the dominant frequency of the soil would be requested. During the Tohoku earthquake, some observed strong ground motions show that their response spectra at pear frequency are 3-4 times larger compared to the safety limit spectra of Japanese Building Code.

International Research Institute of Disaster Science-IRIDeS (formerly Disaster Control Research Center-DCRC) strong motion network (refer to Fig.10) observed not only 2011/3/11 main shock (9.0), but also 2011/3/09 (M7.3) foreshock and 2011/4/07(M7.1) after shock. Table 2 shows outline of the observed records for these earthquake events. During the main shock, the observation records were obtained at 14 stations. The range of PGA values is from 300cm/s/s to 840cm/s/s and that of PGV values is from 30cm/s to 80cm/s. PGA values were large at north part of Sendai city where the soft surface layers deposit on the hard rock. In these sites, dominant period of the ground motion is 0.4s to 0.7s.

Fig.11 shows pseudo velocity response spectra (damping 5%) at Oroshimachi (No.23), Nagamachi (No.25), and Aobyama (No.28) compared to Sumitomo Building near Sendai Station (No.27), which is located on engineering bed rock. The safety limit design spectrum is also shown in this figure. It is found that the period contents less than 1s are amplified by 3 times in Oroshimachi, and that 1s period content at Nagamachi is 4 times amplified in NS direction compared to Sumitomo site and shows the very large response value of 300cm/s. In Aobayama, 1s period content was amplified by two times compared to Sendai Station.

The authors investigated difference of strength demand due to soil conditions based on the observation records obtained in Sendai City and confirmed that strength demand differs 2-3 times for 6-10 story buildings, and about 2 times for 20 story buildings [11].

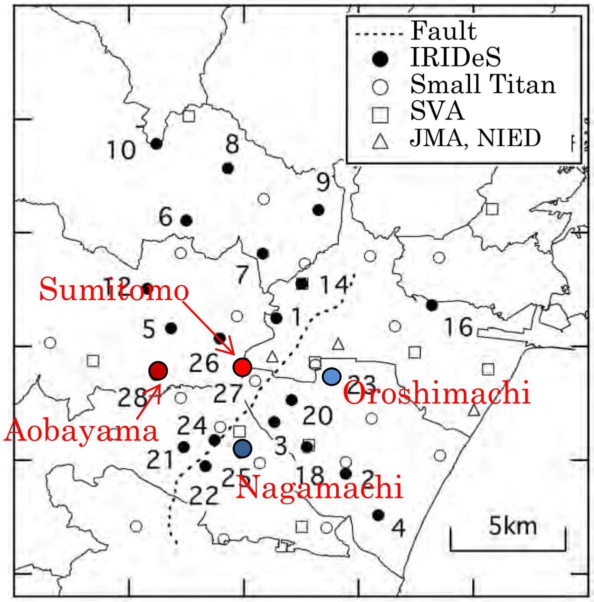


Fig.10 – Site locations of IRIDeS strong motion network

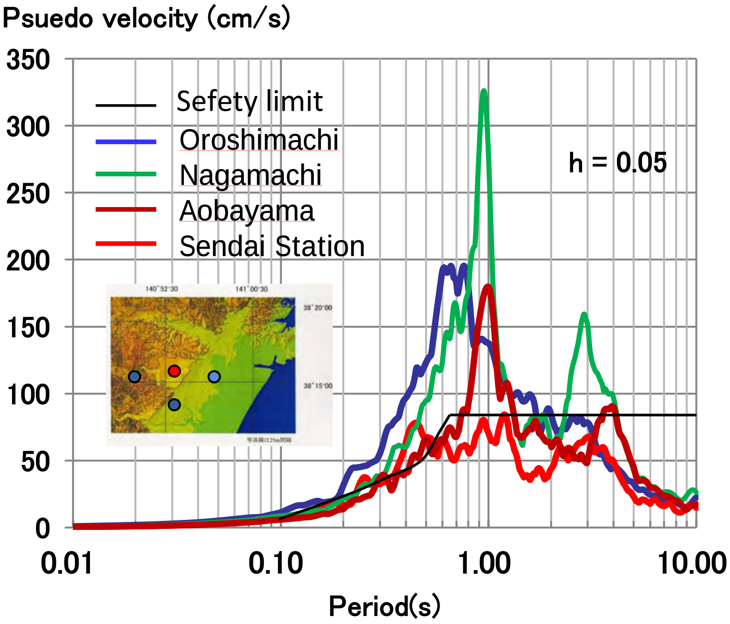


Fig.11 – Comparison of pseudo velocity response spectra due to different soil conditions

Table 2 – Outline of earthquake records by IRIDeS strong-motion network, Tohoku University

			2011/4/7			2011/3/11			2011/3/9		
No	Sensor	Station	PGA (cm/s^2)	PGV* (cm/s)	JMA (Int.)	PGA (cm/s^2)	PGV** (cm/s)	JMA (lnt.)	PGA (cm/s^2)	PGV* (cm/s)	JMA lnt.
2	ETNA	Rokugo Elementary School	311	42.1	5.7	No record			No record		
3	ETNA	Furujiro Elementary School	251	22.4	5.1	320	59.5	5.7	24	3.1	3.3
4	ETNA	Higasi Rokugo Elementary School	Removed			613	74.2	6.0	29	3.4	3.4
5	QDR	Daiiti Jr.High School	230	19.3	5.1	383	39.4	5.6	28	2.9	3.5
8	QDR	Shougenn-Chuoh Elementary School	534	25.3	5.5	840	60.4	6.0	30	2.2	3.2
9	QDR	Matsumori Elementary School	767	75.5	6.2	822	85.7	6.4	46	4.2	3.7
10	QDR	Miyagi Prefecture Library 1F	279	18.0	5.0	407	62.7	5.6	20	2.4	3.2
11	QDR	Miyagi Prefecture Library 3F	No record			No record			34	3.1	3.5
12	QDR	Seiryo Secondary School 1F	No record			No record			19	3.5	3.3
14	QDR	Tsurugaya Elementary School 1F	432	30.6	5.7	No record			20	1.9	3.1
16	QDR	Nakano Jr.High School 1F	No record			No record			40	3.2	3.6
18	QDR	Okino Elementary School 1F	360	31.8	5.6	512	77.6	6.2	37	3.5	3.5
20	QDR	Minami Koizumi Elementary School	220	25.7	5.3	381	63.0	5.6	19	2.4	3.1
21	QDR	Nishitaga Jr.High School	186	16.4	5.0	400	45.1	5.5	23	3.0	3.4
22	QDR	Tomizawa Jr.High School	232	21.1	5.2	416	54.6	5.7	29	3.2	3.4
23	QDR	East Water Supply Center	472	37.3	5.8	613	75.4	6.1	30	2.6	3.3
24	QDR	Ryutaku-Ji	Removed			No record			No record		
25	QDR	Nagamachi Minami Community Center	264	29.5	5.5	494	69.3	6.0	59	6.0	4.0
26	QDR	Aoba Word Office	318	21.9	5.2	No record			24	3.2	3.3
27	SSA-1	Sumitomo Seimei Bldg.	167	14.0	4.9	318	29.2	5.3	15	2.2	3.1
28	SMAC-MD	Tohoku Univ.1F	No record			333	53.7	5.6	35	4.4	3.7
			*cut-off period of 10s,**50s								

3. Specific Features of Building Damage

3.1 Shocking Damage of Retrofitted Building [12]

The research building for Civil Engineering and Architecture & Building Science Department of Faculty of Engineering, Tohoku University (9-story SRC building indicated as hereafter THU building) was damaged severely at the bottom of corner columns at the set backed 3rd floor and demolished. The 'School Building' for graduates of the departments was constructed in 1969 at Aobayama campus on a hill, where the ground motion of 1s period content was amplified 2 times compared to diluvium terrace of central area in Sendai. The response spectral velocity value (damping factor 5%) at around 1s period was 180cm/s. The 8- and 9 story SRC buildings were damaged due to resonance to the amplified ground motion on the hill even though these buildings were retrofitted. The moving resonance phenomenon was recognized based on the non-stationary analysis using the observation records at the 1st floor and the top floor (9th fl.) of THU building. The damage of THU building to which structural engineering specialists were engaged was shocking to Tohoku University. The THU building was damaged but endured well during the 1978 Miyagi-ken Oki earthquake. The building was later retrofitted in 2000.

(a) Damaged coner column bottom (b) Overview (c) Crack at the setbacked 3rd floor

Photo 3 – Damage features of THU building

It is meaningful that the cause of the damage of THU building was scientifically investigated using very valuable observation records of the building together with those at other observation sites in Sendai City. The lessons learned from the THU building are as follows; 1) The hidden damage of main bar's failure at the corner column could not detected, 2) The retrofit work was not appropriate such that earthquake forces were applied to the hidden damage parts, 3) Connection between the replaced shear wall and the existing frame was weak, which lead consequently to partial uplifting of upper part from the 3rd floor of the building.

It is noted that the author's long-term monitoring data of amplitude dependent dynamic characteristics of THU building from completion in 1969 to demolish in 2012 is very valuable in aseismic engineering. It is also noted that the 2 times difference of the ground motion was not applied to the retrofit work, as social acceptance, even though the 2 times amplification of ground motion of around 1s period content was recognized after the 1978 Miyagi-ken Oki earthquake.

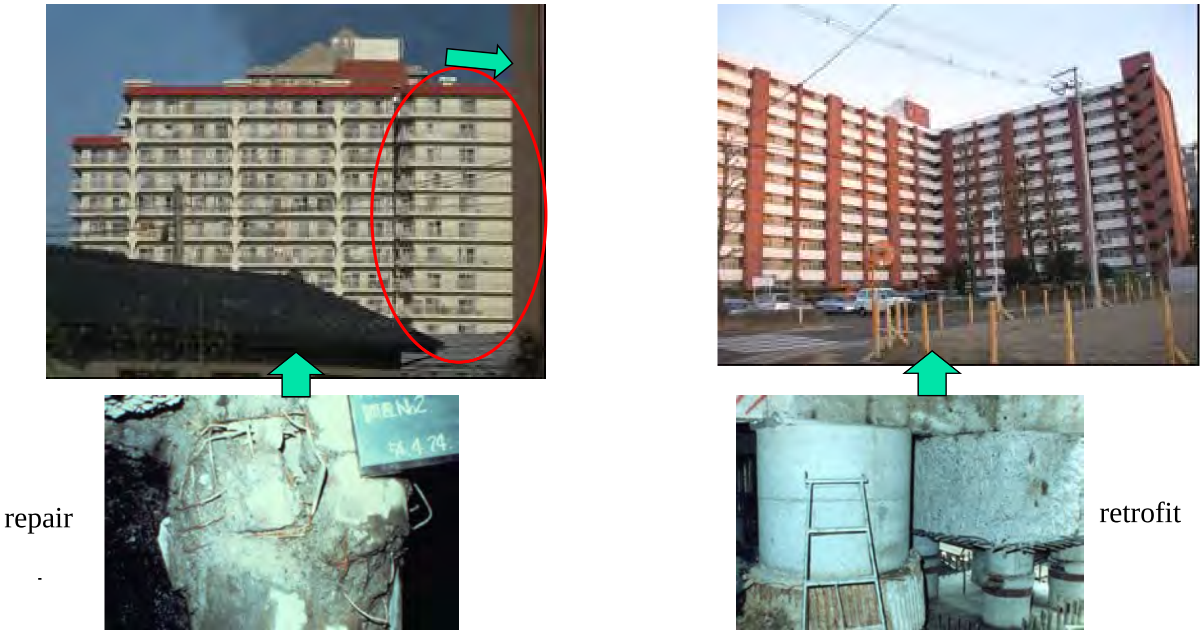
By the way, the earthquake resistance rate of Tohoku University's facilities was 88.5%. The high rate may be related to no human damage but is it noted that the 1st phase of ground motion was very mild. This was not the case of 2nd phase. Namely the amplitude of the 1st phase was gradually increased, which make it possible for persons to evacuate and consequently lead to less human damage. As for the less human damage, the effect of earthquake early warning should be also indicated.

3.2 Necessity of Balance between Super-structure and Foundation

The two buildings with pile foundation damage during the 1978 Miyagi-ken Oki earthquake was divided black and white during the 2011 Great East Japan earthquake. This was due to after treatments of the 1978 earthquake. One is a 14-story SRC building used as a condominium (S-Building) and the other is an 11-story SRC building used for municipal housing (N-Building) [13] (ref. to Photo 4).

In case of the former building, the damaged piles' heads (the two of 7 inspected piles) were repaired by steel rings but it did not increase the seismic resistant capacity of the foundation. This building was toppled by damage of pile foundation during the 2011 Great East Japan earthquake. It is noted that the ground motions of the Great East Japan earthquake is about 30% larger than those of the 1978 earthquake at the same observation point in Sendai.

On the other hand, the latter building toppled by piles' damage during the 1978 earthquake. But after the earthquake, the toppled building could be jacked up and the foundation reinforcement was performed by installation of peers and thick foundation beams. The foundation resistant capacity became larger by 2.5 times. Due to this reinforcement, no structural damage was recognized during the Tohoku earthquake, even though very large shaking (velocity response spectral value of 5% damping is 300 cm/s at around 1s period). At S-building, the consensus building problem among the residence people was raised for the recovery process. The condominium apartment and the municipal apartment were divided into black and white.



(a) S Condominium

(b) Municipal apartment

Photo 4 – The two pile-founation buildings damaged during 1978 Miyagi-ken Oki earthquake devided black and white

As for pile-foundation buildings, seismic capacity of buildings constructed by old building code would be checked especially for those with high aspect ratio.

It is indicated that the pile-foundation damage of the building (K-Building in Oroshimachi, Sendai City) of which super-structure was not damaged during the Great East Japan earthquake, and that of the retrofitted building (F-High School) resulted in demolition. Compared to the adjacent school building (F-Junior High School) of which retrofit was not started yet at that time, the retrofit problem would be considered from the balance of super structure and foundation. A balanced seismic criterion of super structure and foundation is one of important points to be considered.

Counter measures for soil liquefaction against the estimated large earthquakes are also important for pile-foundation buildings.

3.3 Necessity of Balance between Structural Elements, Non-structural Elements and Equipment

As the typical building damage during the Great East Japan earthquake, drop of suspended ceiling board occurred at many multi-purpose halls, local government halls and shopping center and so on, some of which caused human casualty (ref. to Photo 5). It is noted that many halls with ceiling board damage were luckily not in use during the earthquake. The damage problem would not be solved by setting only ‘vibration stopper’ recommended by Ministry of Land, Infrastructure, Transport and Tourism (MILT).

(b) Multi-purose hall in Sendai (a) City office building in Shiroishi

Photo 5 – Damage feature of ceiling board drop

In design of important non-structural elements and equipment, it is recommended to consider the dominant periods of building structure and its supporting soil by adopting the floor response spectra method. It is also important that the vibration energy transmitting from the roof should not propagate horizontally, which leads to wave-like motion of ceiling board [14]. In the case, earthquake load applied to the ceiling board becomes very large compared to that of accumulative area. The regulations of local seismic intensity method would be tightened for important equipment.

As above-mentions, Aobayama campus of Tohoku University was severely damaged. The damage was not only structural damage but also interior equipment such as very expensive experimental equipment (ref.to Photo 6), which leads to huge amount of loss. The reason of the damage is due to extraction of fixture from the wall by long-duration shaking. Consequently, the problem of fixture becomes apparent to verify the safety for the shaking with long-duration.

Photo 6 – Damaged experimental equipment building at Aobayama campus, Tohoku university

Photo 7 – Damaged pent house of a research building at Aobayama campus, Tohoku university

On another thing to be noted is drop of elevators, which occurred in the 8-story SRC research building in the campus. The dropped elevator was supported by wire from the severely damaged penthouse of the building (ref. to Photo 7). There was no issue where responsibility lies because that none was luckily inside of the dropped elevator. For the estimated future earthquakes in other areas, e.g. the Metropolitan area and south-western Japan, the earthquake counter measures for elevators are crucially important. Earthquake early warning can be efficiently utilized for mitigation of the human damage including confinement in elevator.

3.4 Housing Land Damage

During the Great East Japan earthquake, housing lands in Sendai city experienced major damage. Land failures at more than 5,000 points of 9 artificial housing lands were reported. Residence people at one housing land became the situation where they cannot help moving to other place. The common points of the damaged housing lands are valley filled housing land and high water level. These conditioned housing lands were damaged due to a number of cyclic severe shaking with long-duration as shown in Photo 8. The author has indicated that the balance of seismic capacity between the house and its supporting housing land as a member of the Housing Land Committee of Sendai City.

(a) Oritate housing land in Sendai (b) Seikaen housing land in Sendai

Photo 8 – Features of housing land damage

4. Concluding Remarks

In this paper, lessons on building damage from the 2011 Great East Japan earthquake are described in relation to ground motion characteristics. The following learnings and lessons needed to be addressed to establish stronger earthquake countermeasures for urban and building structures.

1) The observed high acceleration record at a K-NET site (MYG004) with maximum acceleration of 2,700 cm/s^2 comprising high frequency content has no power to collapse houses and also topple the unfixed bookshelf.
2) The safety confirmation of building structure in important for cumulative response long-duration ground motion and many aftershocks. A case study indicated that cumulative response due to many past earthquakes is larger than that of main shock of the huge earthquake. From this point, the residue performance of buildings damaged by past earthquakes and this earthquake needs to be evaluated.
3) Ground motion characteristics due to the huge earthquake are quite different depending on geological conditions. Soil amplification should be enforced in seismic design possibly including seismic micro-zoning.
4) As for specific building damage buildings, a retrofitted 9-story SRC building damage was introduced. Ground motion amplification in the hilly zone and the induced resonance phenomena is strongly related to the severe damage considering the non-stationary nature of ground motion and the nonlinearity of the building should be considered.

5) A total balance of the structural elements, the non-structural elements, and the equipment needs to be established. Also, the balance of foundation and the superstructure for the synthetic seismic performance of the whole building needs to be achieved.

6) Huge numbers of housing land damage were caused at valley filled place with high water level together with number of displacement cycles due to the huge earthquake. Strong houses become in vain for housing land failure.

By the way, it is important to utilize efficiently many observation data during the huge earthquakes and to verify the correspondence of observation and analysis based on observation data including structural health monitoring data, which is not described in this paper.

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