PERFORMACE OF SEISMICALLY ISOLATED BUILDINGS
DUE TO 2011 TOHOKU EARTHQUAKE

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Abstract

The Great East Japan Earthquake (Tohoku Earthquake) that occurred in 2011 caused serious damage to a widespread area. The human damage and number of buildings drowned out by the tsunami were great, and there were many cases where old buildings were damaged by the shock of the earthquake. However, most seismic isolated buildings were not severely damaged and fully showed the effect of their performance. The large ground motions caused by this earthquake that hit across a wide stretched area, from the Kanto area to the Tohoku area, lasted for a longer period of time than any of the past. The effects that long-duration ground motions have on the response of seismic isolated buildings and the characteristics of seismic isolated devices were verified by a seismic response analysis of seismic isolated buildings. Furthermore, a comparison with the earthquake motions that had been observed inland of Japan verified the characteristics of Tohoku earthquake.

Introduction

In Japan, more than 2600 seismically isolated buildings have been constructed. The seismic isolation technology has been applied to office buildings, condominiums, hospitals and detached houses. In order to obtain the optimum isolation effect, various devices (rubber bearing, sliding bearing, roller bearing, hysteresis damper, oil damper, etc.) are used in combination.

After 1995 Kobe earthquake, National Research Institute for Earth Science and Disaster Prevention (NIED) deploys the digital strong-motion seismograph (K-net & Kik-net) across the all of Japan. The collected seismic data analyses are made available to the public on the Internet. On 11 March 2011, Great East Japan Earthquake (Tohoku Earthquake) occurred. After the main shock, several earthquakes occurred. The main shock was recorded at more than 900 stations of K-net & Kik-net.

The observed maximum acceleration during the Tohoku Earthquake was 2.7G in horizontal direction and 1.8G in vertical direction. The duration time of the observed records was much longer than the near fault earthquake such as Kobe earthquake. In the Tohoku region hardest hit by this earthquake, there were many seismic isolated buildings. Almost all seismic isolated buildings were safe and show their performance. The response of seismic isolated building was estimated by dynamic response analysis using the observed records.

In this paper, the observed earthquake records of seismic isolated buildings were introduced. The response of seismic isolated buildings due to the observed earthquake records was studied in comparison with the response of the buildings caused by earthquakes in the past, such as 1995 Kobe earthquake, 2004 Niigata earthquake, etc.

Observed Earthquake Records

The number of seismic isolated buildings has been increasing dramatically, since the 1995 Great Hanshin-Awaji Disaster (Kobe earthquake). The number of detached houses with seismic isolation has been increasing from 2000 due to the revised standard of buildings. Figure 1 shows the number of buildings with seismic isolation. The first seismic isolated building was built in 1982. After Kobe earthquake, the

number of isolated buildings increased dramatically and has been maintained at around 170 buildings each year. Half of them are apartment house. Remarkably, almost all hospitals which have been built after 1995 have a seismic isolation system.
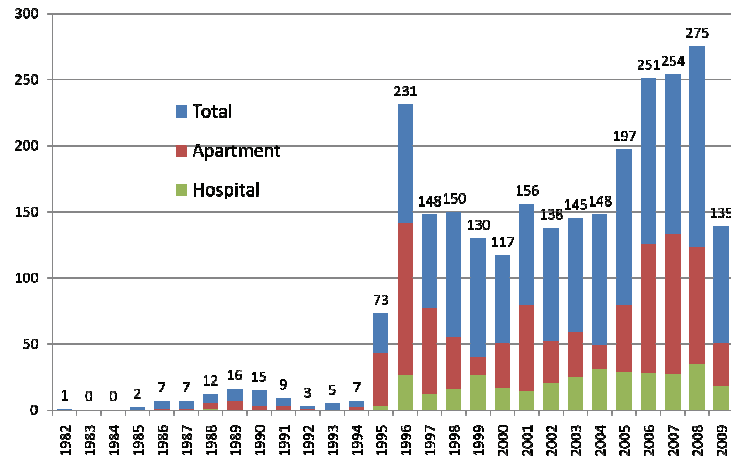

Figure 1. Number of Seismic Isolated Buildings in Japan (the detached houses are not included)

Table 1 shows the top 15 of the observed earthquake records of seismic isolated buildings during the 2011 Tohoku Earthquake. The table shows the use of buildings, isolation systems, the maximum acceleration observed, and the maximum deformation of the seismic isolation layer measured (a Blank space indicates no measurement). The types of buildings include an office, a hospital, an apartment, a school etc. and the stories of the buildings vary from 2 to 26. Among the isolation systems used there, there are simple systems using only high-damping rubber or lead rubber bearing. Also, there are isolation systems combined with sliding bearing and various types of damper along with laminated rubber bearing. In every case, the most optimum system was selected in order to achieve the seismic isolation performance, which was the goal of the design.The maximum acceleration obtained in these buildings was 756 gal, which was recorded in a seismic isolated building of two stories in Fukushima Pref. The maximum deformation of the seismic isolation layer was more than 20 cm in the Tohoku districts of Miyagi Pref. and Fukushima Pref., and they were less than 10 cm in the Kanto Districts of Tokyo and Chiba pref. The deformation of a seismic isolation layer of more than 40 cm was observed in a three-story building in Miyagi Pref., which is not shown in this table. At any rate, it was revealed that seismic isolated buildings fully showed the effect of their performance.

Figure 2 shows the maximum response accelerations observed in all seismic isolated buildings. The horizontal axis of these figures shows the maximum acceleration at the basement of the seismic isolation layer. The vertical axis of Figure 2(a) shows the maximum acceleration at 1st floor or roof of the building. The vertical axis of Figure 2(b) shows the ratio of the maximum accelerations (amplification factors) of the 1st floor (1FL) and the highest floor (Top floor) against that of the basement of the seismic isolation layer. From all observed results, it is revealed that the accelerations of the superstructure were more greatly damped than those of the basement (input acceleration) and that the larger the escalation of the basement, the greater the effect of seismic isolation becomes.

But the amplification factor is greater than 1.0 when the input acceleration is small. Only the response observed in the direction of Y of the roof of the building No.15 in Table 1(a) is amplifying 2.2 times. It is considered because the local response of the beam in which the seismograph was installed was added to this observed value. Although the response of the direction of Y in the roof of this building was greatly amplified with 250gal, the directions of X were 126gal of that half. The building No.53 in Table 1(b) is also amplifying the first floor or the roof to the input acceleration of 301gal. The reason is considered because the design isolation period is as short as 1.67 seconds (Cuadra, 2012).

Table 1. Observed Earthquale Records of Sesimic Isolated Buildings during 2011 Tohoku Earthquake

(a)The Top 15 of order with a Small Amplification

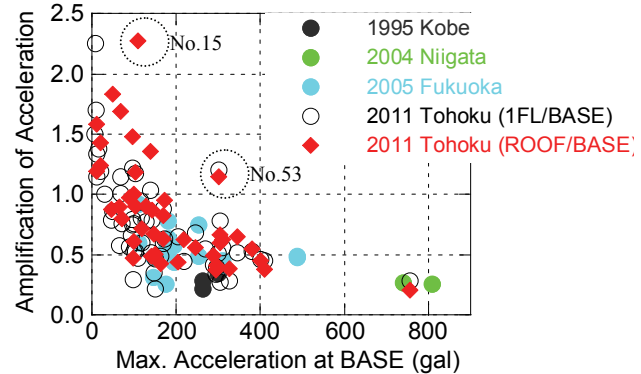| No.	Prefecture	Use	Story	Isolation System*	Max. Acceleration (gal)			Amplification		Max. Displacement (cm)
					BASE	1FL	ROOF	1FL/BASE	ROOF/BASE	
1	Tokyo	Office	2	RB+VD	151	33		0.219		
2	Iwate	Hospital	6	NRB+LRB+SLB+SD	305	83	183	0.273	0.599	9.4
3	Ibaragi	Office	7	NRB+LRB+SD	327	92	126	0.281	0.385	5.9
4	Fukushima	Office	2	NRB+LRB+SLB+OIL	756	213	155	0.282	0.205	24.0
5	Tokyo	School	26	NRB+OIL	98	29	46	0.296	0.469	7.7
6	Ibaragi	Office	6	NRB+SLB+OIL	295	101	110	0.341	0.373	10.0
7	Kanagawa	School	7	HDR	147	51	99	0.347	0.672	6.8
8	Ibaragi	Research Lab.	3	NRB+SD+LD	296	117	121	0.395	0.409	5.6
9	Miyagi	Office	9	HDR+OIL	289	121	142	0.419	0.491	18.0
10	Miyagi	Office	9	NRB+LRB	289	121	142	0.419	0.491	15.1
11	Chiba	Office	8	NRB+HDR	219	98	137	0.445	0.626	4.7
12	Fukushima	Office	3	LRB+SLB+OIL	411	184	154	0.448	0.375	
13	Ibaragi	Apartment	21	NRB+SLB+SD+LD	402	185	181	0.460	0.450	13.9
14	Chiba	Apartment	3	NRB+VD	150	70	75	0.467	0.503	7.8
15	Tokyo	Research Lab.	2	HDR	110	52	250	0.473	2.273	7.7

(b)The Top 15 of order with a Large Acceleration at BASE

No.	Prefecture	Use	Story	Isolation System*	Max. Acceleration(gal)			Amplification		Max. Displacement (cm)
					BASE	1FL	ROOF	1FL/BASE	ROOF/BASE	
4	Fukushima	Office	2	NRB+LRB+SLB+OIL	756	213	155	0.282	0.205	24.0
12	Fukushima	Office	3	LRB+SLB+OIL	411	184	154	0.448	0.375	
13	Ibaragi	Apartment	21	NRB+SLB+SD+LD	402	185	181	0.460	0.450	13.9
20	Miyagi		6	HDR	381	200	209	0.525	0.549	18.1
18	Miyagi	Office	5	HDR	345	177	224	0.513	0.649	10.5
3	Ibaragi	Office	7	NRB+LRB+SD	327	92	126	0.281	0.385	5.9
24	Miyagi	Office	18	NRB+SLB	311	173	194	0.557	0.624	23.0
2	Iwate	Hospital	6	NRB+LRB+SLB+SD	305	83	183	0.273	0.599	9.4
37	Ibaragi	Research Lab.	5	NRB+LD	305	238	203	0.780	0.666	18.9
53	Miyagi	Research Lab.	3	HDR	301	362	344	1.203	1.143	11.5
17	Miyagi		9	NRB+LRB	299	152		0.508		8.0
8	Ibaragi	Research Lab.	3	NRB+SD+LD	296	117	121	0.395	0.409	5.6
6	Ibaragi		6	NRB+SLB+OIL	295	101	110	0.341	0.373	10.0
9	Miyagi	Office	9	HDR+OIL	289	121	142	0.419	0.491	18.0
10	Miyagi	Office	9	NRB+LRB	289	121	142	0.419	0.491	15.1

* NRB: Natural Rubber Bearing, HDR: High Damping Rubber Bearing,
LRB: Lead Rubber Bearing, SLB: Sliding Bearing
OIL: Oil Damper, SD: Steel Damper, LD: Lead Damper, VD: Viscous Damper
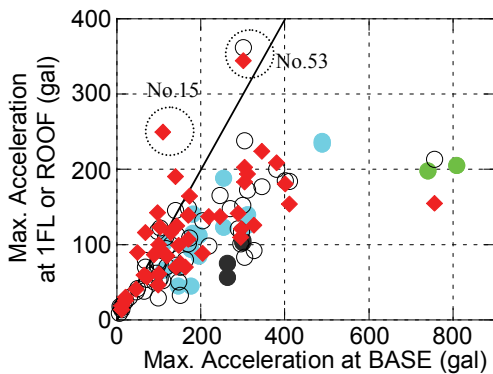
(a)The Observed Max. Acceleration (b)Amplification Factor

Figure 2. The Observed Acceleration of Seismic Isolated Buildings

Characteristics of Observed Earthquake Records

National Research Institute for Earth Science and Disaster Prevention (NIED) deploys the digital strong-motion seismograph (K-net & Kik-net) across the all of Japan. The collected seismic data analyses are made available to the public on the Internet. On 11 March 2011, Tohoku Earthquake occurred. After the main shock, several earthquakes occurred. The main shock was recorded at more than 900 stations of K-net & Kik-net. Table 2 shows the peak acceleration at 7 stations including the station recorded the maximum acceleration (station code: MYG004) among the main shock. At the several stations, the peck acceleration was over 1G.

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Table 2. Maximum Acceleration Records due to Tohoku Earthquake (unit: gal)

Prefecture	Station Code	Location	NS-dir.	EW-dir.	UD-dir.
Miyagi	MYG004	Tsukidate	2699.9	1268.5	1879.9
	MYG010	Ishinomaki	458.2	377.0	332.0
	MYG013	Sendai	1517.2	982.3	290.2
	MYG015	Iwanuma	410.7	353.2	253.9
	MYGH10	Yamamoto	870.8	852.7	622.2
Tochigi	TCG006	Ogawa	377.6	376.1	181.2
Fukushima	FKS020	Inawashiro	241.5	275.6	96.0

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Figure 3 shows the acceleration wave observed at MYG004 station. The envelope of that wave is unusual. The main shock occurred 2 times due to this earthquake. The duration time is much longer than the near fault earthquake such as Kobe earthquake.

Figure 4 shows the response spectra of observed waves shown in Table 2. There are three response spectra of: velocity spectrum (5% damping), energy spectrum (10% damping) and displacement spectrum (20% damping). The energy spectrum was proposed by Akiyama(1985), which can be obtained by earthquake energy input into elastic vibration system of 10% damping being calculated. The vertical axis of (b) of the figure shows the energy input by earthquake being converted into equivalent velocity. The displacement spectrum is calculated presuming a 20% equivalent damping constant of seismic isolated buildings.

The MYG004 wave that recorded the largest acceleration among the observed waves showed a very high response in the neighborhood of a 0.2 second period, but it showed smaller responses than other observed waves for more than 1 second periods. In velocity spectrum and energy spectrum, the MYG010 wave and TCG006 wave showed high responses at more than 1 second period. In the displacement spectrum, these waves showed high responses exceeding 30 cm in the range of from a 2 second period to a 4 second period, and the MYG015 wave showed the highest response. Following these, the FKS020 wave also showed a high displacement response. This is because the observation point of the FKS020 wave was on soft ground, so that the observed wave included many long-period components.

Before 2011 Tohoku Earthquake, several earthquakes had resulted in damage to buildings, such as the 1994 Northridge Earthquake, the 1995 Kobe Earthquake, the 2004 Niigata Chuetsu Earthquake, the 2007 Chuetsu-Oki Earthquake, and the 2008 Iwate-Miyagi Inland Earthquake. Figure 5 shows the response spectra by observed waves of these earthquakes. Although the earthquake motions shown here were of short duration, the maximum velocities were over 100 cm/s. The velocity spectra exceeded 200 cm/s in the range of from a 1 second period to near a 3 second period, and some of them exceeded 400 cm/s at the maximum. The displacement spectra with a damping ratio of 20% showed the response of over 40 cm at more than 2 second periods, and those of large earthquake waves exceeded 60 cm. The design displacement of many seismic isolated buildings designed in Japan is around 40 cm, and the clearance up to the retaining wall is often around 60 cm. In the case where these strong earthquake motions are input, it

will become necessary to presume situations such as collision to the retaining wall, fracturing of laminated rubber bearing, etc. It is revealed that the maximum response deformation of the seismic isolated buildings during the 2011 Tohoku Earthquake was small compared with the response by these earthquake motions
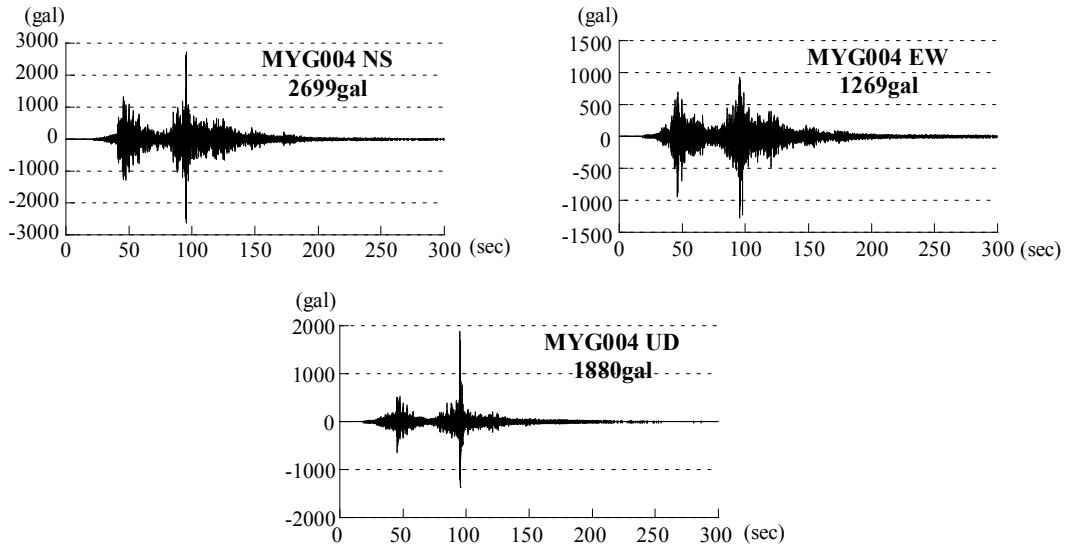

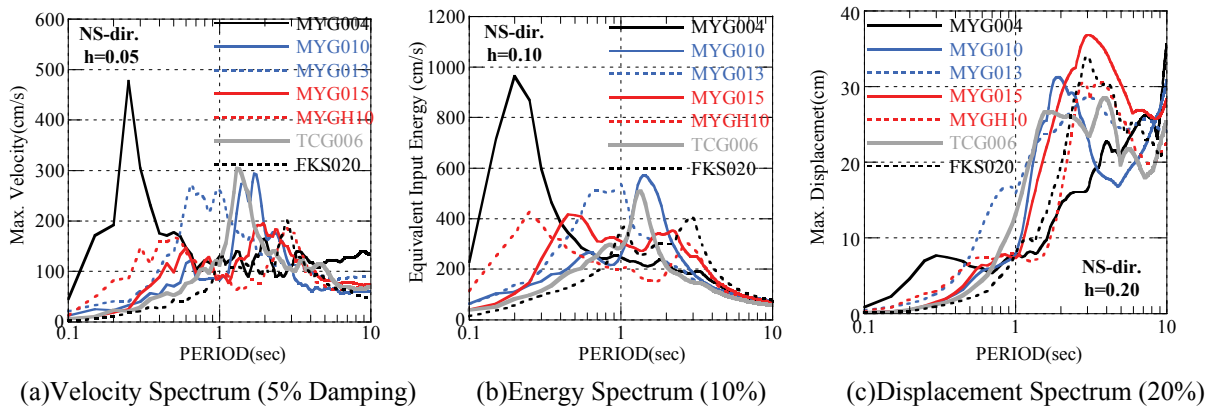*Figure 3. Acceleration Records of MYG004*

(a)Velocity Spectrum (5% Damping)　　(b)Energy Spectrum (10%)　　(c)Displacement Spectrum (20%)

Figure 4. Response Spectra of 2011 Tohoku Earthquake

(a)Velocity Spectrum (5% Damping)　　(b)Displacement Spectrum (20%)
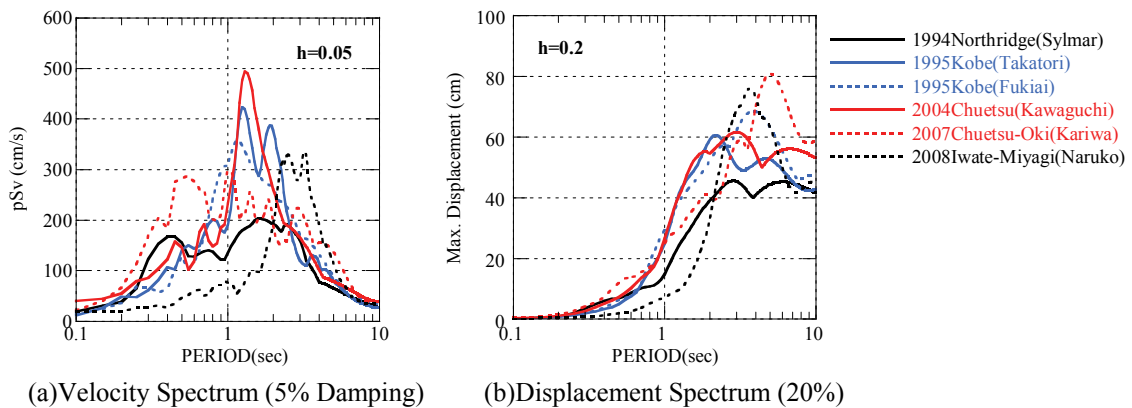
Figure 5. Response Spectra of Near fault Earthquake

Response Analysis of Seismic Isolated Buildings

Analytical model The analytical model used was a single-degree-of-freedom model, and the characteristic of the seismic isolation layer was presumed to be restoring force characteristics of bi-linear type, as shown in Figure 6. Viscous damping was not taken into account. The seismic isolation period, T_d, and yield shear coefficient, α_s, in Eq.(1) are important factors for the response evaluation of seismic isolation buildings. The seismic isolation period here was presumed as the period based upon the stiffness after yield, and it was varied in the range of from approximately 1 sec. to 10 sec. The yield shear coefficient is the rate of yield load against the total mass, M, of a building, and its range was presumed to be 0.02-0.05. The yield displacement was presumed as constant at 1 cm.

$$T_d = 2\pi \sqrt{\frac{M}{K_d}} \quad , \quad \alpha_s = \frac{Q_d}{Mg} \tag{1}$$

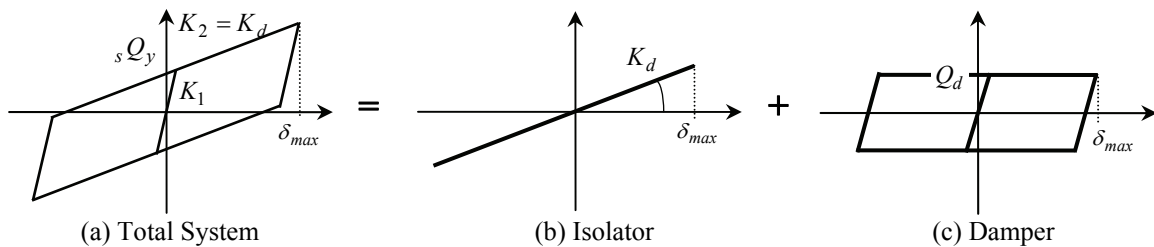(a) Total System   (b) Isolator   (c) Damper

Figure 6. Restoring Force Characteristic of Analytical Model

Analytical results The results of seismic response analysis of seismic isolation buildings are shown in Figures 7, 8 and 9. Figure 7 shows the maximum response displacement of seismic isolation layers, Figure 8 the accumulated displacements, and Figure 9 the maximum shear coefficients. The horizontal axis of each graph shows the seismic isolation period, and the yield shear coefficient, α_s, of a damper shows the three cases of 0.02, 0.03 and 0.05. The reason why responses are large at the periods of less than 2 seconds is that, because the periods are short, the hysteresis damping is small. In the cases where the seismic isolation period is more than 4 seconds, the maximum response displacement and accumulated displacement are stable. When the damping is small (α_s is small), the responses of the MYGH10 wave and FKS020 wave become large in the neighborhood of a 3 second period. However, their peaks become smaller with larger α_s.

The maximum response displacements of the MYG015 wave and MYG013 wave were largest at around 40 cm. The MYG004 wave, which showed a very large response value in the range of short periods in the velocity response spectrum (Figure 4), shows the maximum displacement at approximately 20 cm. Through all the analytical results, the maximum displacements of approximately 50 cm are shown at the periods of about three seconds, but the maximum displacements become approximately 40 cm at periods of more than 4 seconds.

Accumulated displacement is related to the energy absorption capacity of a damper, so that it provides an indication of evaluating energy absorption capacity. The longer the seismic isolation period is, the smaller the accumulate displacement becomes. The accumulated displace is 30 m at the maximum in the neighborhood of a 3 second seismic isolation period, and it is reduced to around 10 m if the period becomes longer. There are large differences according to the kinds of earthquake wave, too. The

MYG010 wave does not largely change, caused by the yield shear coefficient, α_s, of a damper, and shows approximately 10 m at periods of more than 3 second seismic isolation periods.
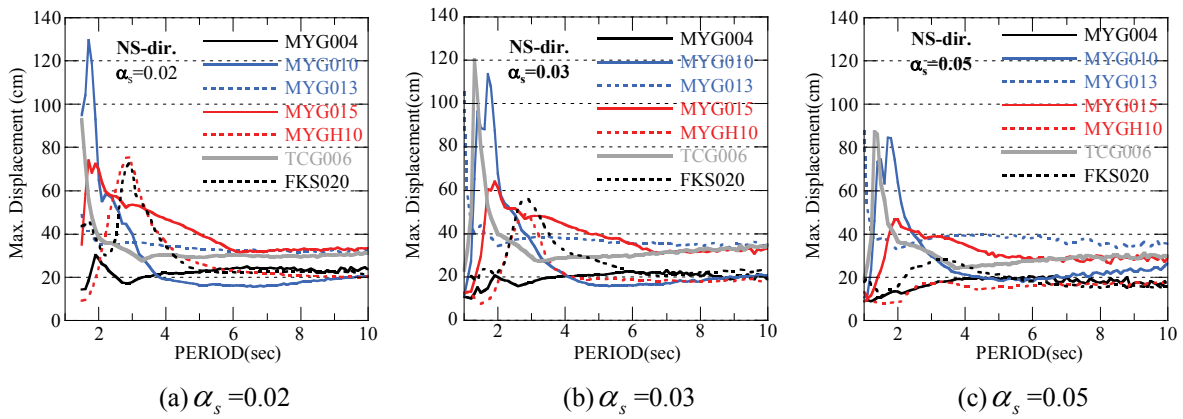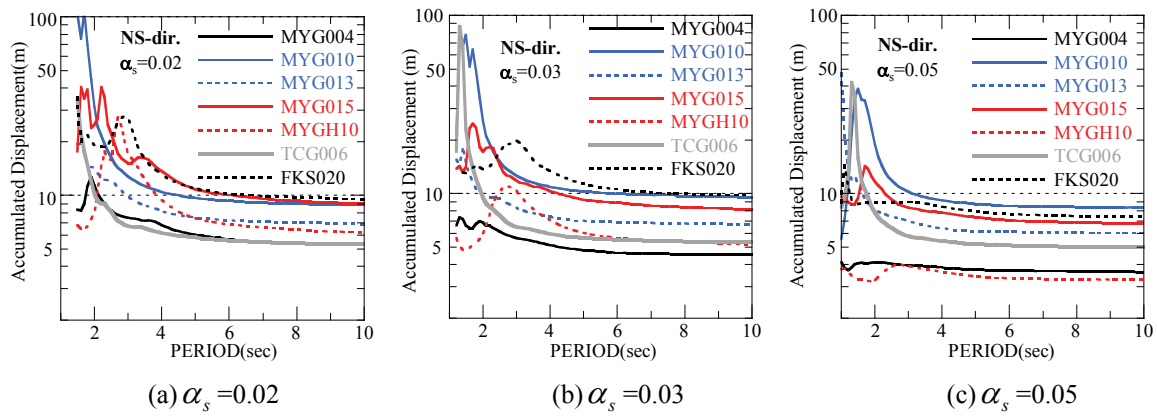

Figure 7. Maximum Response Displacement

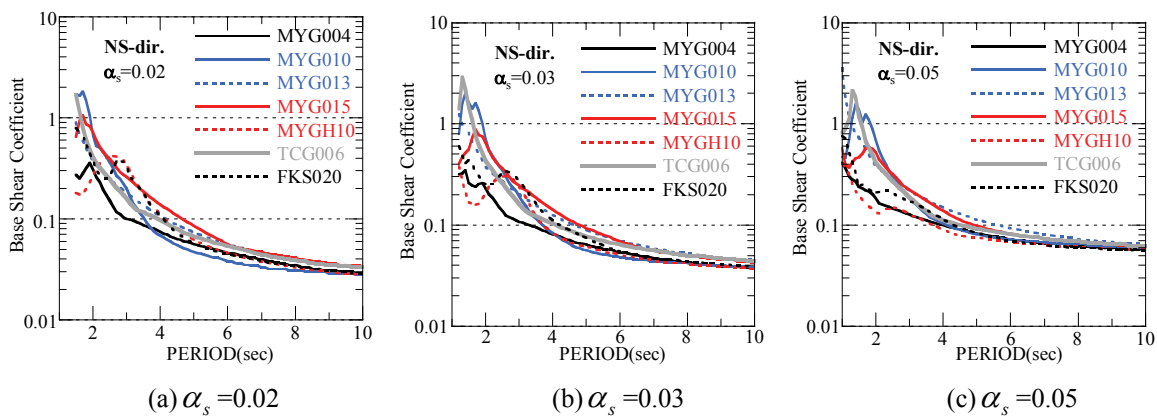*Figure 8. Accumulated Displacement*

Figure 9. Base Shear Coefficient

The longer the seismic isolation period is, the more the maximum yield shear coefficient of seismic isolation layer reduces, and the larger the yield shear coefficient becomes, the larger the maximum yield shear coefficient of seismic isolation layer becomes. The shear coefficient falls below 0.1 when the seismic isolation period is over 4 seconds. In order to reduce the shear coefficient when the seismic isolation period is short, it may be necessary to add an oil damper, etc.

CONCLUSIONS

In this paper, the seismic response analyses of seismic isolation buildings were implemented using the earthquake waves that were considered to greatly affect the seismic isolation buildings from many records observed from the 2011 Tohoku Earthquake. Also, the earthquake waves were compared with those observed in the past.

The maximum response displacement of seismic isolation buildings caused by 2011 Tohoku Earthquake is considered to 30 cm-40 cm, and this is consistent with the records obtained from the earthquake observation. Compared with the earthquake observation records of the past, the duration time of the earthquake wave of this earthquake was long and many aftershocks followed, so that many repeated deformations affected the isolation systems. It is necessary to verify the energy absorption capacity of seismic isolation devices. In some seismic isolation devices, the yield load decreases and the energy absorption capacity deteriorates along with repeated deformation. Therefore, it is required to properly take such characteristics into account at the structural design stage.

References

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C.H. Cuadra et al. (2012), Evaluation of the Dynamic Characteristics of a Base-Isolated Low-Rise RC Building after the Great East Japan Earthquake, Proc. of 15WCEE, Paper No.1248, 2012