

# Development and Application of Seismic Isolation and Response Control of Buildings in Japan

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**ABSTRACT:** The number of seismically isolated buildings in Japan has increased dramatically since the 1995 Kobe earthquake and the total number now exceeds 4000. The seismic isolation technology has been applied to office buildings, condominiums and hospitals. Additionally, the number of detached houses with seismic isolation has reached 5000. 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, 2004 Niigata earthquake (M6.8), 2005 Fukuoka earthquake (M7.0) and 2011 Tohoku earthquake (M9.0) occurred. Many earthquake records of seismically isolated buildings have been obtained. The positive effects of seismically isolated buildings were shown by the analyses of these earthquake records.

As with seismic isolation, similar advances have been made in response control technologies for buildings in Japan. Response control systems are classified into either passive or active, where active also includes semi-active systems. Currently in Japan, most seismic response control systems that have been applied to buildings are passive systems. About 70 active and semi-active control systems have already been applied to actual buildings in Japan since 1989. The response control systems have been applied for enhancing safety of high-rise and super high-rise buildings. The total number of response controlled buildings exceeds 1200.

This paper introduces the development and practical application of seismic isolation and response control of buildings in Japan and also observation data records during earthquakes to verify the performance of these buildings.

## 1 INTRODUCTION

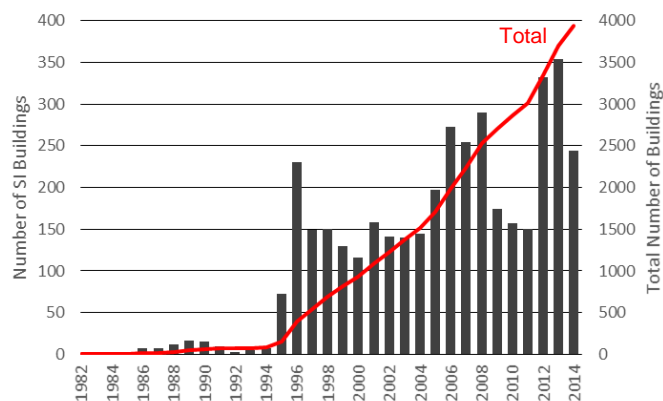
In Japan, more than 4000 seismically isolated buildings are constructed. The number of seismically isolated buildings has been increasing, since the 1995 Great Hanshin-Awaji Disaster (Kobe Earthquake). The seismic isolation technology has been applied to office buildings, condominiums, hospitals and 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, 2004 Niigata earthquake (M6.8), 2005 Fukuoka earthquake (M7.0) and 2011 Tohoku earthquake (M9.0) occurred. Many earthquake records of seismically isolated buildings have been obtained. The positive effects of seismically isolated buildings are shown by the analyses of these earthquake records. But the several buildings were damaged in the expansion (seismic gap) area. In Tohoku earthquake, the duration time of recorded earthquake waves was 2 to 3 minutes. Energy absorption performance of the isolation devices must be verified. This issue has been tackled for several years by dynamic cyclic experiments of rubber bearings and hysteresis dampers etc..

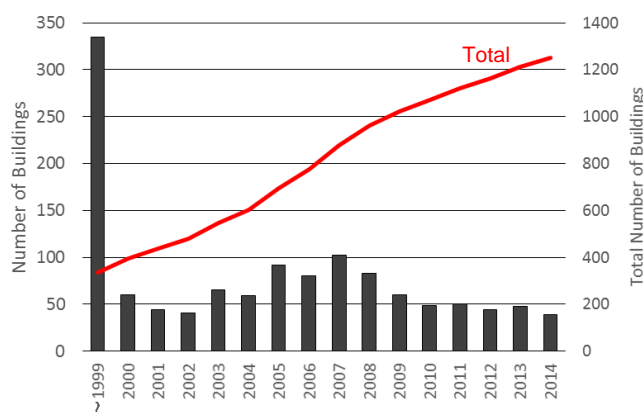
In this paper, the present situation of seismic isolation technology in Japan is described and the earthquake records obtained in the seismic isolated buildings are also shown.

## 2 PROFILE OF SEISMICALLY ISOLATED BUILDINGS

The number of seismically isolated buildings in Japan has increased dramatically since the 1995 Kobe earthquake and the total number now exceeds 4000 (Figure 1). The seismic isolation technology has been applied to office buildings, condominiums and hospitals. Additionally, the number of detached houses with seismic isolation has reached 5000. 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. Many earthquake records of seismically isolated buildings have been obtained. The positive effects of seismic isolated buildings were shown by these earthquake records.



**Figure 1. Number of Seismically Isolated Buildings in Japan (Source: JSSI)**



**Figure 2. Number of Passive and Active Control of Buildings in Japan (Source: JSSI)**

As with seismic isolation, similar advances have been made in response control technologies for buildings in Japan. Response control systems are classified into either passive or active, where active also includes semi-active systems. Currently in Japan, most seismic response control systems that have been applied to buildings are passive systems. About 70 active and semi-active control systems have already been applied to actual buildings in Japan since 1989 [1]. The response control systems have been applied for enhancing safety of high-rise and super high-rise buildings. The total number of response controlled buildings exceeds 1200 (Figure 2).

## 3 GREAT EAST JAPAN EARTHQUAKE

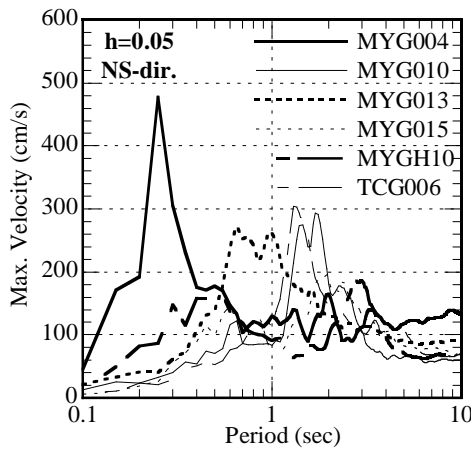
### 3.1 Characteristics of Observed Earthquakes on the Ground (Free Field)

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

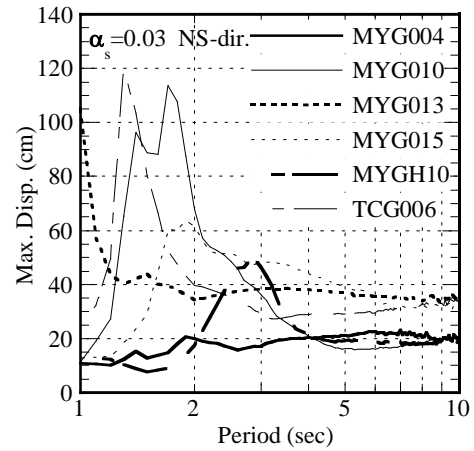
main shock was recorded at more than 900 stations of K-NET & KiK-net. Table 1 shows the peak acceleration at 6 stations including the station recorded the maximum acceleration (station code: MYG004) among the main shock. At the several stations, the peak acceleration was over 1G.

**Table 5. Maximum Acceleration Records due to Great East Japan Earthquake (unit: gal)**

Station Code	Location	NS-dir.	EW-dir.	UD-dir.
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
TCG006	OGAWA	377.6	376.1	181.2



**Figure 3. Velocity Spectra of Great East Japan Earthquake**



**Figure 4. Maximum Displacement of Seismic Isolation Model**

Figure 3 shows the velocity spectra (damping factor: 0.05) of the observed earthquake records shown at Table 1. MYG004 show the maximum velocity of 480 cm/s at 0.25 sec of period. The spectra at MYG010 and TCG006 show the peak at around 1.5 sec of period.

In the Tohoku region hardest hit by this earthquake, there are many seismically isolated buildings. Almost all seismically isolated buildings were safe and show the good performance. The Japan Society of Seismic Isolation (JSSI) made the report of the detailed information about the performance of seismically isolated building and response control buildings during this earthquake.

The response of seismically isolated building was estimated by dynamic response analysis using the observed records shown in Table 1. The seismically isolated building was simply modeled as the single-degree-of-freedom model with the restoring force characteristics of bi-linear type. The yield deformation of bi-linear characteristics was constant value of 1cm. The yield force can be calculated by multiplying the yield shear coefficient to the weight of the model. Though it depends on the magnitude of the design earthquake and the design displacement of isolation level, the yield shear force coefficient is often used in a range of 0.02 to 0.04 in the building design. The second stiffness (post-yield stiffness) of the bi-linear characteristics was related to the period of the seismic isolation. The second stiffness was calculated as the period varies from 1 to 10 sec.

Figure 4 shows the maximum displacement of the seismically isolated model in case of the yield shear coefficient of 0.03. The horizontal axis of this figure shows the period based on the second stiffness of bi-linear model. In the period range of 1 to 2 sec, the response of MYG010 and TCG006 is very large. In the period over 4 sec, the maximum response is less than about 45 cm. The design displacement of the seismically isolated buildings is usually 40cm in Japan especially after Kobe earthquake.

Considering that these seismic waves were observed at the free field on the ground, the actual seismic response of the seismically isolated buildings is likely to be smaller the values shown in Figure 4.

### 3.2 Earthquake Records of Seismically Isolated Buildings and Passive Control

The observed earthquake records were obtained from seismically isolated buildings and the building with passive energy dissipation systems in Tokyo and Tohoku region during the Great East Japan Earthquake.

From among many buildings, the observed records of three buildings using a new technology are introduced in this section. One building is a tall building using the semi-active control technology; another is a 3 story building with 3-dimensional isolation technology; last one is the seismic retrofitting high-rise building by use of oil damper.

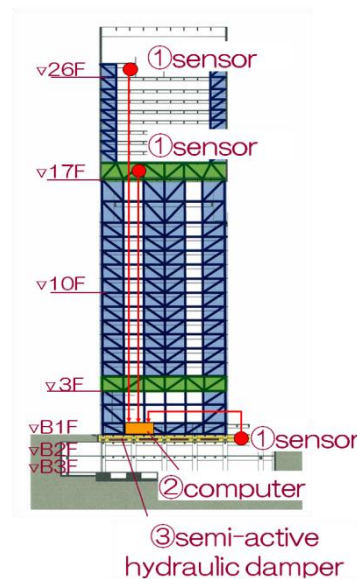
#### (1) Semi-Active Isolated Building

The tall building with semi-active isolation system is 26 stories high [2][3]. The base isolation system for this building consists of natural rubber bearing (maximum diameter: 1500 mm) and oil damper. All energy absorption on the base isolation level is accomplished by the oil damper. There were 24 units of oil damper in both X and Y direction. 12 units of these are variable oil dampers and 12 units are passive oil dampers. The variable oil dampers are able to switch the damping coefficient between two stages. The high level damping coefficient of the variable oil damper was about 3 times greater than the low level damping coefficient. The results of the complex eigen-value analysis of this building are shown in Table 2. The damping factor is about 20% in the case of low level damping, and over 35% in the case of high level damping.

**Table 2. Eigen Value of Semi-Active System**

	First Period (sec)	Damping Factor
High Level Damping	4.6	0.35 to 0.39
Low Level Damping	5.2	0.22 to 0.24

The sensors have been set at the superstructure and isolation level, and constantly observe the motion of the building (Figure 5). The observed acceleration and displacement are transmitted instantly along the connection cables to the controller. In the event of earthquake, the controller puts the ideal control signals, in accordance with pre-programmed control rules, to switch the damping coefficient of the variable oil dampers. The control is conducted regardless of the scale of the earthquake to reduce the acceleration of the superstructure.



**Figure 5. Semi-active Isolation System and Sensor Location**

**Table 3. Maximum Acceleration of Semi-Active control building (unit: gal)**

story	X (Transverse)	Y (Longitudinal)	Z (Vertical)
26F	46.1	50.9	234.6
17F	66.0	34.1	87.4
B1F	29.2	31.7	43.8
MB2F	97.7	63.6	40.1

Table 3 shows the maximum acceleration of the observed records during the Great East Japan Earthquake. Maximum acceleration is about 98 gal under the isolation level. The response acceleration of superstructure is about 30 gal to 66 gal. The response ratio is about 1/3 to 1/1.5.

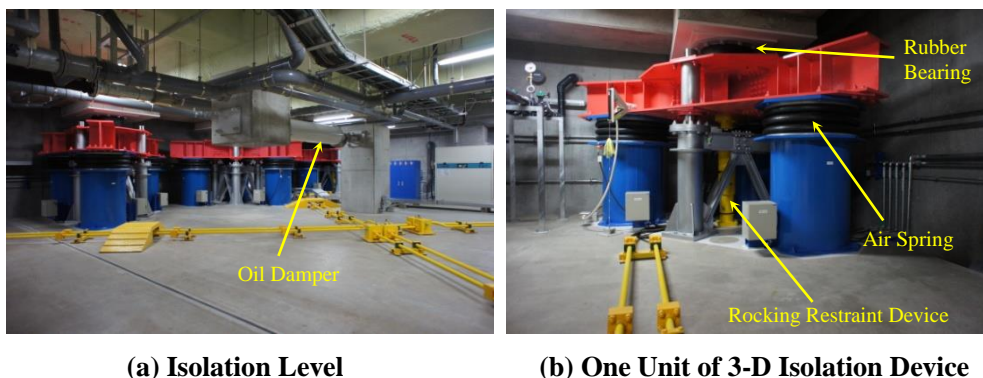
## (2) 3-D Isolated Building

The seismically isolated buildings are generally effective only in the horizontal direction. As indicated in previous sections, the vertical response of superstructure often amplified than the input acceleration. However, 3-D seismic isolation system have been developed and applied to the 3 storied residential building (Figure 6) [4].



**Figure 6. 3-D Seismically Isolated House**

The 3-D seismic isolation system consists of 3-D isolation units (8 units), oil damper (3 units) and restraint device of rocking motion of the building (Figure 7). The 3-D isolation units have the high damping rubber bearing for the horizontal isolation, and the air spring for the vertical isolation shown in Figure7(b). The period of this building is 2.9sec in horizontal direction, and 1.3 sec in the vertical direction.



**Figure 7. 3-D Isolation System**

Table 4 shows the maximum acceleration of the observed records. The response acceleration of the superstructure has been reduced from input acceleration in both horizontal and vertical direction.

**Table 4. Maximum Acceleration of 3-D Isolation House (unit: gal)**

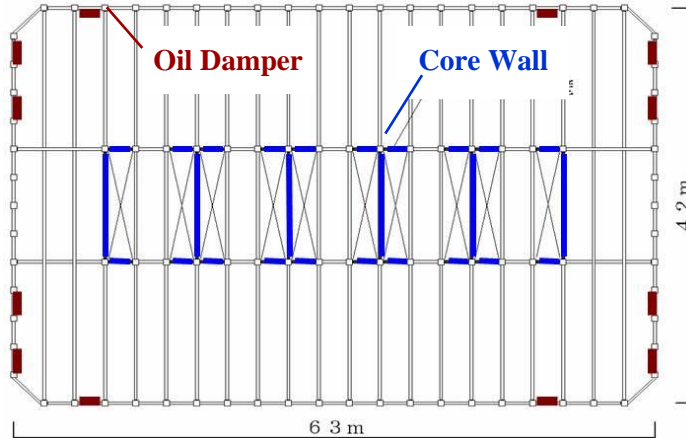
Story	NS-dir	EW-dir	Vertical
1st Floor	49.9	49.1	33.2
Basement	89.5	81.2	46.0

### (3) Seismic Retrofit Building using Oil Dampers

The seismic retrofitting using oil dampers was applied to the existing 54-story office building (Sinjuku Center Building) [5]. This building was constructed in 1979. The first natural period of this building is 6.5sec in transverse (Y) direction and 5.4 sec in longitudinal (X) direction. Figure 8 shows the typical floor plan. 12 units of oil damper in every 24 floors from 15th floor to 39th floor were installed based on the results of dynamic response analysis. The oil damper was installed between bottom of brace and girder as shown in Figure 9. The total number of oil damper was 288.

Table 5 shows the observed maximum acceleration at 2011 Tohoku earthquake. The maximum acceleration of the roof floor was 236gal and the maximum displacement was 54.2cm. The average story drift angle was 1/399. There were no damages on the main structure such as columns and girders. The maximum deformation of the oil dampers during the earthquake was between 5mm to 15mm.

The vibration control effect of the retrofitting building was verified by simulation analysis. Dynamic analysis was conducted by the mode superposition method with considering up to the 10th mode. For 1st to 3rd mode, the damping ratio which was identified from the observed seismic records was used. For over 3rd mode, the damping ratio was constant. From the analysis results, the maximum response with oil dampers showed a decrease of 20% of the maximum response without oil dampers.

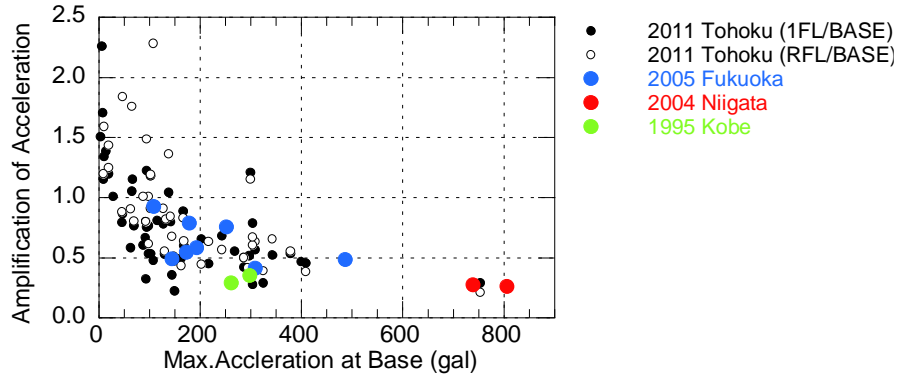
**Figure 8. Typical Floor Plan****Figure 9. Installed Oil Damper****Table 5. Maximum Acceleration and Deformation of Retrofitting Building**

Story	Max. Acceleration (gal)		Max. Deformation (cm)	
	Longitudinal (X)	Transverse (Y)	Longitudinal (X)	Transverse (Y)
RFL	236.0	161.3	49.4	54.2
28F	112.7	171.3	26.3	33.3
1F	94.3	142.1	-	-

### (4) Summary of Observed Maximum Acceleration

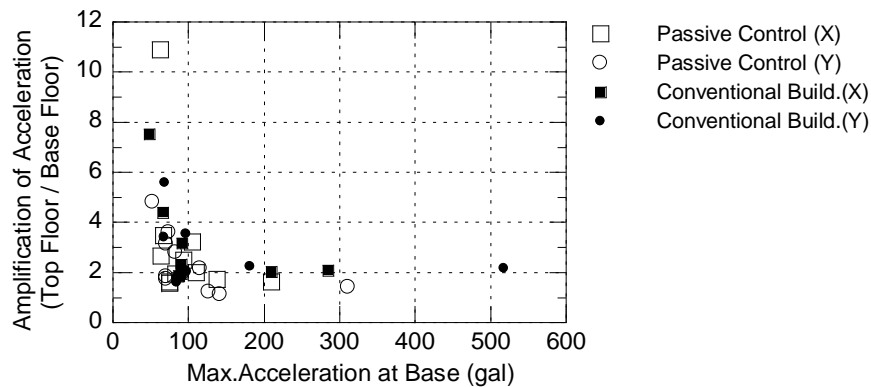
Figure 10 shows the maximum response accelerations observed in seismically isolated buildings. In

this figure, the observed records obtained from over 60 buildings with seismic isolation system have been shown. The horizontal axis of this figure shows the maximum acceleration at the basement of the seismic isolation level, and the vertical axis shows the ratio (amplification factors) between the maximum accelerations of the superstructure (1st floor or top floor) and the basement of the seismic isolation level. From all observed results, it is revealed that the acceleration response of the superstructure has been greatly reduced. In particular, the greater the acceleration of the basement as the isolation effect becomes larger. If the acceleration of basement is less than 100 gal, the amplification factor is often greater than 1.



**Figure 10. Amplification Factor of Observed Acceleration of Seismically Isolated Buildings**

Figure 11 shows the maximum acceleration observed in the conventional buildings (7 buildings) and the buildings with passive energy dissipation systems (11 buildings) during 2011 Tohoku earthquake. The passive control devices were used such as steel damper, buckling restrained brace, oil damper. Because the level of earthquake input was small, there is no noticeable effect of passive control compared to conventional buildings.



**Figure 11. Amplification Factor of Observed Acceleration of the Buildings with Passive Energy Dissipation Systems and Conventional Buildings**

#### 4 CONCLUSIONS

This paper presents the results of the earthquake observation of the seismically isolated buildings and response control buildings. The effect of seismic isolation system has been demonstrated by seismic records. There was no damage in the superstructure of seismically isolated buildings. Although damage was seen in some of the hysteresis dampers due to energy absorption, seismic isolation system was functioning as expected in the design.

In the observed record of 2011 Tohoku earthquake, the effect of vibration control was not clear. It is very important to collect such the seismic observation records as it is necessary for the better development of seismic isolated structures and response control buildings.



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