CURRENT STATE OF SEISMIC-ISOLATION DESIGN

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ABSTRACT:
Japan has the highest number of seismic-isolation structures in the world. The number of such structures has been gradually increasing since the Hanshin-Awaji Disaster in 1995. It is the main reason that seismically isolated buildings have shown good performance during and after earthquakes. As people are becoming aware of the benefits of the seismic isolation system, it is being accepted more, in order to maintain structural safety and functionality during and after earthquakes. Items for life safety, property value, and maintaining functionality should be satisfied in the performance level of protection of buildings against big earthquakes. This system is the appropriate earthquake-resistant method in consideration of satisfying these three items, and positive in the design of structures, such as houses, hospitals, and high-rise buildings, then in retrofitting. The current state of seismically isolated structures and recent problems on the design for seismic isolation systems are discussed here.

KEYWORDS:
seismic-isolation, safety, functionality, isolator, damper

1. SEISMIC ISOLATION PROFILE IN JAPAN

Japan has suffered many disastrous earthquakes. Many condominiums and detached houses were damaged in the 1995 South Hyogo prefecture earthquake, and the collapse of several hospitals shocked people. The structural design strategy of “Seismic Isolation (SI)” is a technology capable of substantially mitigating seismic disaster. Seismic Isolation provides opportunities for flexible, diverse, and highly earthquake-resistant designs. It also controls both acceleration and story drift of the superstructure during an earthquake.
More than 900 SI condominiums and 3,000 SI detached houses were constructed after the quake. Almost all new hospitals after the above mentioned earthquake have been planned with SI. The total number of buildings and houses with SI system in Japan is more than 5,000 (table 1). There is no prefecture without an SI building; However most of the buildings with SI system are located in the Tokyo Metropolitan area, which has the highest occurrence of earthquakes in Japan.
The largest SI Housing Estate in the country, site area (120 m by 300 m), is Kamikuzawa Condominiums in Sagamihara city, Kanagawa prefecture in the Kanto area (shown in figure 1). Prof. T. Funakoshi and his partners planned and designed the huge housing site consisting of 21 buildings on an artificial base, seismically isolated by 242 isolators.

Table 1 Summary of SI buildings in Japan

Total number of SI buildings:	2,000	1983 to 2007
Ratio for condominiums: (High-rise condominiums:)	45% (6%)	 (Increased from 2000)
Ratio for SI buildings in Kanto area:	45%	Tokyo has the highest percentage at 20%.
Ratio for retrofitting:	4%	
Annual number of isolators:	6,000	Manufactured, 2004 to 2007
Annual number of dampers:	1,000	manufactured, 2004 to 2007
Total number of SI detached houses:	3,000	1996 to 2007

About 80 buildings, most of which were completed mainly after 1950 have been retrofitted by SI systems.

Business was conducted as usual in about half of these buildings during construction for retrofit.[8)]
A very significant trend is gradual increase in the use of SI systems in high-rise-condominiums (figure 2), over the last ten years. The ratio of SI high-rise-buildings constructed is shown in table 1.

The largest SI Housing Estate was designed by ARCOM R&D Architects, Structural Design Group Co., Ltd. and Dynamic Design Inc.

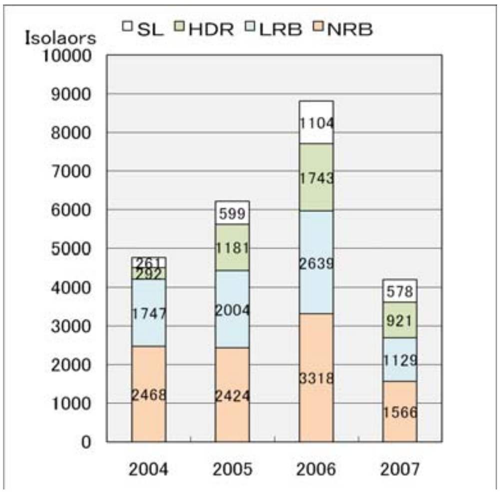
Figure 1 Kamikuzawa Condominiums in Sagamihara city, Kanagawa prefecture

The large isolators are installed as 28 NRB, 1,500 mm diameter, with 15 SD, and 44 LD, MM Towers were designed by Mitsubishi Jisho Sekkei Inc.

Figure 2 High-rise condominiums with SI, MM towers, Yokohama city, Kanagawa prefecture

The structural design method is mostly by using “Time-History-Analysis” (THA), which is a dynamic analysis to attain the value of response displacement or acceleration against earthquake vibration directly. However, very

recently, the Equivalent Linearized Method has been used (although rarely) with some legislated stipulations. Almost all buildings were calculated by THA in Japan. There are codes and several standards for structural design, and JSSI cooperates with the government in creating these.[1,2,3,4,5,6,7)]
Meanwhile, the usage of isolators and dampers produced recently is shown in figures 3 and 4. 6,000 isolators are manufactured annually, including high-damping rubber bearings (HDR) and sliders with elastomer and PTFE (SL), and 1,200 dampers are being manufactured annually, including oil dampers (OD). It is very common for structural engineers to use natural rubber bearings (NRB) as isolators. The usage ratio is 65 % including lead plug embedded rubber bearings (LRB), and hysteretic dampers as steel rods (SD) and lead rods (LD). The usage ratio of these is 50 % among structural engineers in Japan.



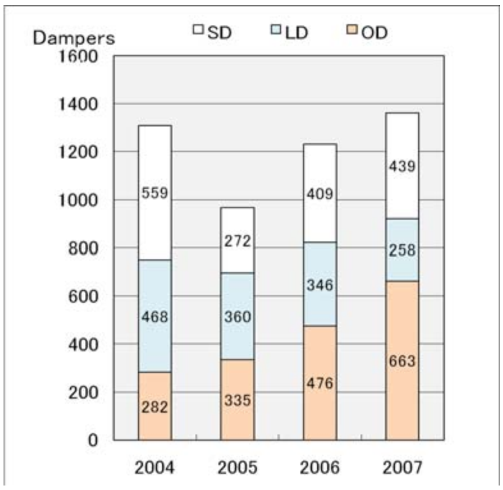


Figure 3 Number of isolators manufactured　　Figure 4 Number of dampers manufactured

2. PERFORMANCE OF SI BUILDINGS

The number of SI structures has been gradually increasing for three reasons: several severe earthquakes have occurred in the past decade shown in table 2, and a notification for seismic-isolation (SI) buildings was issued by MLIT in Oct. 2000. From the many recent earthquakes in Japan, positive results have been shown by analyzing seismographic records of SI buildings. SI buildings were stout and stable during and after earthquakes.

Table 2 Recent earthquakes

Quake Name	Magnitude	Date
The Tokachi-Offshore quake	8.0	Friday, Sept. 26, 2003, 04:50
The 2004 Niigata Chuetsu quake	6.8	Saturday, Oct. 23, 2004, 17:56
The 2005 Fukuoka West-Offshore quake	7.0	Sunday, Mar. 20, 2005, 10:53
The 2007 Noto Hanto quake	6.9	Sunday, Mar. 25, 2007, 09:41
The 2007 Niigata Chuetsu-Offshore quake	6.8	Monday, July 16, 2007, 10:13
The 2008 Iwate-Miyagi Inland quake	7.2	Saturday, June 14, 2008, 08:43

2.1. The Tokachi-Offshore quake

JSSI members surveyed the situation of buildings with SI after the above earthquakes occurred. Several surveys were done on buildings with SI in Kushiro city (table 3). These buildings showed good performance. All reports described that nothing fell from shelves or desks in these buildings, and there was no damage to the buildings (Building A to D). The movements of seismic isolation section were around design level. The effects of seismic isolation (reduction ratios) were one-fourth to two-third, according to the acceleration ratio of the base to the superstructure. Many occupants felt very slow vibrations.

Table 3 List of buildings in Kushiro city[9,10,11,12,13)]

Name	Story	Usage	Structure	Substructure Devices
Building A	3	Office	RC	Mat LRB
Building B	9	City Hall	SRC	Mat+Pile NRB+SD, LD 140km
Building C	7	Bank	SRC	Mat+Pile NRB+SD, LD
Building D	3	Hospital	RC	Mat HDR

2.2. The 2004 Niigata Chuetsu quake

After the Niigata-Chuetsu earthquake, JSSI committee members visited buildings with SI in Niigata (table 4). These buildings also showed good performance. The secretary general at a health care facility for the aged said that nothing fell from shelves, and there was no damage in the building. This building became a shelter for people from Ojiya hospital facilities, which had been damaged.

Table 4 List of the building in Niigata prefecture[14,15,16,17)]

Name	Story	Usage	Structure	Substructure Devices
Building A	5	Health Care	RC	Mat NRB+ SL 6km
Building B	2	Data Center	S	Mat NRB 20km
Building C	8	School	RC	Mat HDR+SL 20km

The movement of the seismic isolation section of this facility (Building A) was around 140mm from a skid trace of the slider with elastomer. The effects of seismic isolation (reduction ratios) were one-fourth, according to the acceleration ratio of the base to the superstructure, by an installed seismograph.

The information center for computer service (Building B) was built as an internet data center in Nagaoka city, completed on Sept. 1 2004, and business began in October. The structural calculation was in accordance with Notification No. 2009 (by the equivalent linearized method). The relative displacement of the seismic section during the earthquake was about 80 mm, by the orbiter. There was no damage. Some of the workers stayed there for a couple of days, using it as a shelter.

The structure of Hokuriku Vocational School (Building C) is RC with high damping rubber bearings. The CEO said that there was nobody in the school at the time of the earthquake. The next day, they found nothing unusual in the building; Nothing fell and none of the furniture or household articles had fallen. They experienced many aftershocks in this building, which they said felt like riding a boat. They are very satisfied with the seismic isolation system in their building. About 200 mm displacement of the seismic isolation section of this school was measured. The effect of seismic isolation is shown as one-fourth reduction by an installed seismograph.

2.3. The 2005 Fukuoka West Offshore quake

Before the Fukuoka West-Offshore earthquake, the most recent one of significance in the city area was in 1898. Prof. M. Takayama reported that response displacements of most buildings were less than the equivalency of 50 cm/s-design level, but nothing fell down or moved in buildings with seismic isolation. Buildings listed in table 5 were surveyed.

The manager of the dormitory (Building A) was right at the front entrance at the time of the earthquake. He thought that the movement was from a nearby JR freight train railway. Nothing fell from shelves.

The transformation of the seismic isolation section of these condominiums (Building B to E) was small because of the distance from the epicenter. A resident who lives on the eighth floor of the building felt almost no movement.

The 7-story building (Building F) is in the vicinity of the Kego fault. The maximum response displacement of the seismic isolation section reached about 300 mm.
A seismograph was installed in this building; Acceleration indicated about 200 gals of NS component at 65 m

below ground, and about 500 gals at base. Seismic isolation effect is one-half, or about 250 gals at seventh floor.

The seismograph installed in a 9-story office building (Building G) recorded a maximum acceleration in the base of about 150 gals, but about 70 gals at the roof level. The observed displacement was 145 mm. Acceleration of the superstructure was reduced to between one-half and one-third.
The clerk of this building said that nothing fell from shelves and his perception of the vibration was very small in the office on the top floor.

Table 5 List of buildings in Fukuoka city[18,19)]

Name	Story	Usage	Structure	Substructure Devices		
Building A	4	Dormitory	RC	Mat	HDR	
Building B	14	Condominium	RC	Piles	NRB+SD+LD	
Building C	14	Condominium	RC	Piles	LRB	
Building D	12	Condominium	RC	Piles	LRB	
Building E	6	Condominium	RC	Piles	HDR	
Building F	7	Office	RC	Piles	HDR	
Building G	9	Office	SRC	Piles	NRB+SD+LD	25km
Building H	11	Hospital	SRC	Mat	NRB+SD+LD	
Building I	13	Hotel	RC	Piles	NRB+SD+LD	
Building J	10	Office	S	Piles	NRB+SL+LD	

An inpatient on the sixth floor in a large hospital (Building H) said that he felt vibrations, but that nothing fell down or moved. The displacement of the seismic isolation section was about 150 mm. The maximum repetition was almost 2 cycles was traced. Observed acceleration was reduced to one-half.

This hotel (Building I) is located about 600 m from the fault. As for the trace in the seismic isolation section, displacement was at a maximum of about 100 mm.
According to a hotel clerk, the vibration during the earthquake was slow.
There were several guests there at the time of the Earthquake, but they did not express any fear about the shaking of the building. The elevators stopped for about five minutes, but resumed automatically, and nothing fell down or moved.

This office building (Building J) of steel construction is located about 200 m west of the fault. According to a clerk, nothing fell down or moved.

2.4. The 2007 Noto Hanto quake

After the Noto Hanto earthquake, the following buildings were surveyed by JSSI members (table 6). The fire station (Building A) in Nanao city is located 30 km from the epicenter, and about 100 mm movement was shown by the trace of expansion joints without the measurement of seismographs.
Personnel in the fire station said that although nothing fell down, power failure occurred, but was restored automatically by a generator of its own.

Table 6 List of buildings in Ishikawa prefecture[20)]

Name	Story	Usage	Structure	Substructure Devices		
Building A	5	Fire Station	RC	Mat	NRB+ LD	30km
Building B	5	Fire Station	RC	Mat	NRB+ SD, LD	
Building C	2	Research Inst.	RC	Mat	FPS(Friction Pendulum System)	

A fire station (Building B) in Kanazawa city moved slightly less than 10 mm. It is located 70 km from the epicenter, and it shifted slowly.

The Research Institute of Magara Construction (Building C) is located 80 km from the epicenter. The orbiter indicated a few mm displacements with acceleration reduction as one-half.

The effects of seismic isolation, and the satisfaction and dissatisfaction of occupants have been verified. The abovementioned experiences of the people should be considered in the design of buildings with seismic isolation for a performance based concept.

2.5. The 2007 Niigata Chuetsu-Offshore quake

Observed records of the health care facility for the aged (Building A, table 7) again showed good performance in the Niigata Chuetsu-Offshore earthquake. The effects of seismic isolation (reduction ratios) were one-half, according to the acceleration ratio of the base to the superstructure.

The orbiter of the information center for computer service (Building B, table 7) in Nagaoka city again showed a relative displacement of less than 40 mm in the earthquake.

Table 7 List of the building in Niigata prefecture[21,22]

Name	Story	Usage	Structure	Substructure Devices		
Building A	5	Health Care	RC	Mat	NRB+ SL	40km
Building B	2	Data Center	S	Mat	NRB	30km

2.6. The 2008 Iwate-Miyagi Inland quake

Activities of this hospital shown in table 8 and figure 5 did not cease at all during or after the severe earthquake. Many people felt a slow shifting of the building, but neither employees nor inpatients were injured. Doctors and nurses were able to cope with the treatment of the people injured in the earthquake. The commercial electrical service failed in the earthquake, but the backup power generation started automatically. The hospital served as the local disaster protection center. Response displacement was about 90 mm from traces of rod movements of oil dampers.

Table 8 List of buildings in Kurihara city[23]

Name	Story	Usage	Structure	Substructure Devices		
Building A	4	Hospital	RC	Mat	NRB+ OD	45km

The hospital was designed by Seki Kukan Sekkei Architects, and Kozo Keikaku Engineering Inc., 183 NRB with 70 OD are installed.

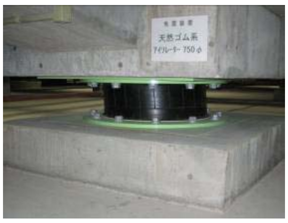


Figure 5 Kurihara city central hospital, Kurihara city, Miyagi prefecture

3. PROBLEMS WITH SI SYSTEMS

The first SI house in Japan was built in 1983. It was not until about ten years ago that the first high-rise SI building was constructed in Japan. However, since then the number of such buildings has been increasing every year.

The effect of SI systems has been positive in many occurrences of earthquakes over the last two decades, and

structural engineers have been improving SI systems since 1980.
However, the following problems related to SI systems must be solved in order to provide better structures.

3.1. Problems for structural design

・ Recently in Japan, seismic waves of long period components and of long duration have been discussed among structural engineers and researchers. These seismic wave properties directly affect SI systems, especially damping devices. Analyses will be needed to ensure the safety of buildings for each damper, based on the data received through tests in factories related to long period and long duration of seismic waves. Performance of dampers for energy dissipation mainly related to thermal deterioration and durability of cyclic use must be checked and disclosed to structural engineers.

・In the connecting parts of devices fixed to the structure, anchorage parts were broken in a recent earthquake in Fukuoka prefecture, due to a design and construction defect. The design details of the parts of installed devices, which are expected to achieve good performance, are important. Scrupulous detail design guidelines regarding the connection parts of devices and the periphery parts of the SI section will be required.

・Conventionally, structural rigidity for frames of superstructures with SI is sufficiently stiffer than the rigidity for SI sections with devices, but recently several buildings with SI have been designed with low rigidity, especially in high-rise structures with SI. When the seismic isolation ratio is low, response accelerations are not reduced much in buildings with SI. Insufficient rigidity of the superstructure of buildings with SI should be discussed much more among structural engineers.

・Performance tests of large-size elastomeric isolators should be carried out. In the case of large size elastomeric isolators, it is difficult to directly determine the properties of the isolators by using Japanese device manufacturers' own testing machines. These testing machines are not sufficient for tests of the largest size elastomeric isolators (1,600 mm as diameter). No Japanese factories have large scale testing machines. It is needed to develop the appropriate equation to show the properties of a large-size isolator on the basis of the testing data of middle-size isolators or to execute tests by a huge machine, which can be found in other countries.

・According to appearance of SI high-rise buildings and lightweight wooden houses with SI, wind response and characteristics of the device for seismic isolation became apparent against typhoons and seasonal winds. There are problems for a perception of people for movements of building and for energy absorbing capacity of devices, during wind blowing both for long duration and cyclic loads.

3.2. Problems related to near-future systems

・High-durable elastomeric isolators will be requested near future. High durability of elastomeric isolators is appropriate to sustain the 200-year durable housing systems which are the new action plan based on a proposal by Prime Minister Fukuda. MLIT started pushing this plan in 2008.

・Seismographic monitoring of vibration of SI buildings during earthquakes should be done. Several buildings with SI have seismographic monitoring instruments installed for the purpose of gathering information regarding the properties of SI during earthquakes; However the number of such buildings is low. Moreover, monitoring is especially needed to capture the characteristics of SI buildings, which will be reflected in the following structural design. Continuation of long-term observation of SI systems by seismographs is important. Observation results gained through installed instruments are valuable in order to know the properties of SI systems during earthquake vibration. These instruments must be installed in SI buildings that will be constructed in the near future.

・New systems such as SI systems with semi-active control to be used in the near future should be developed. SI systems must be much more feasible to accomplish performance based design with response control systems in the near future, in order to orient direction to control the behavior of structures by using response control devices with a stable computer system.

・More dissemination should be done for future expansion of SI buildings. Although there are benefits of seismic isolation systems, very few people know what they are. More dissemination and expansion of public relations about SI must be carried out for structures to be able to maintain basic performance, such as securing human life, preserving property and maintaining functionality of buildings and to provide seismic protection during and after earthquakes. Particularly, the performance of SI buildings after earthquakes must have favorable evaluations for business continuity planning.

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