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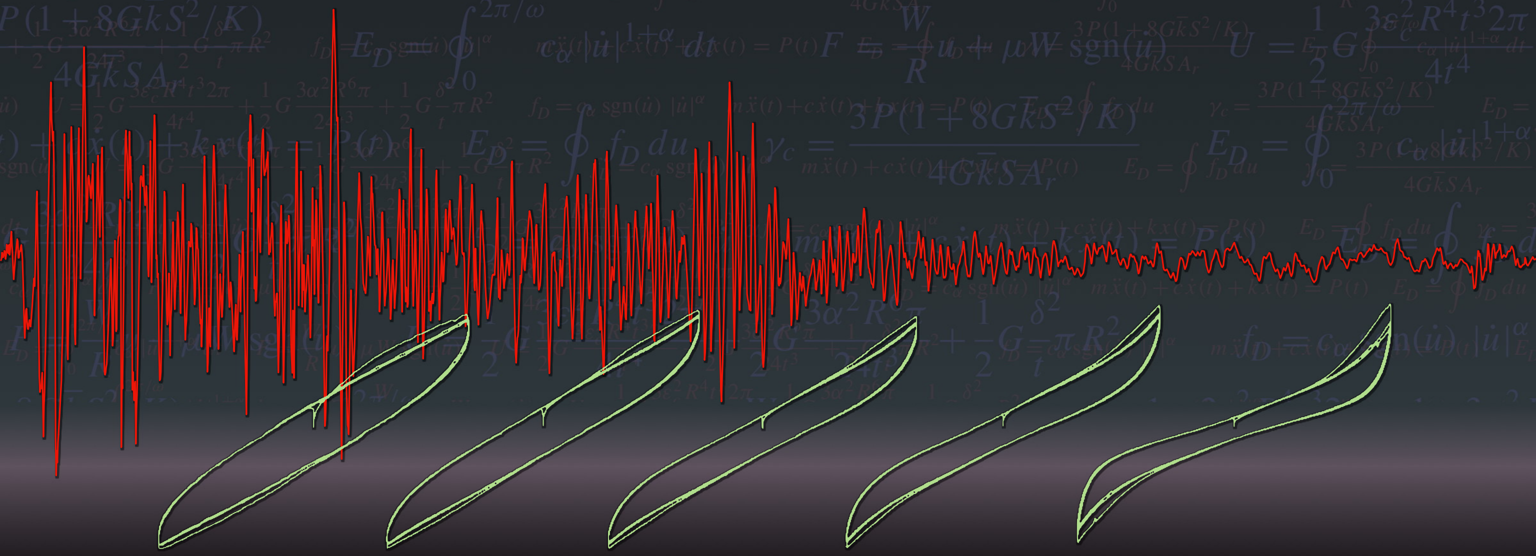

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REPORT ON THE EFFECTS OF SEISMIC ISOLATION METHODS FROM THE 2011 TOHOKU–PACIFIC EARTHQUAKE

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The earthquake that occurred on March 11, 2011 off the Pacific Coast of Tohoku caused devastating damage to the northeast Pacific coast region of Japan. We discuss the response to this earthquake of three buildings in Shimizu Corporation's Institute of Technology in Tokyo, each with a different type of seismic isolation, and that of a test building for seismic isolation jointly built by Shimizu Corporation and Tohoku University on the Sendai campus in Miyagi prefecture, which was near the earthquake's epicenter. The effects of seismic isolation methods were verified through the observed earthquake responses of the four buildings. In each of the three seismic isolated buildings at the Institute, the observed accelerations on the floors were reduced to about half compared to those on the ground. In the test seismic isolated building in Tohoku University, the observed accelerations on the roof were reduced to about one third compared to those in an adjacent conventional seismically designed building.

1. Introduction

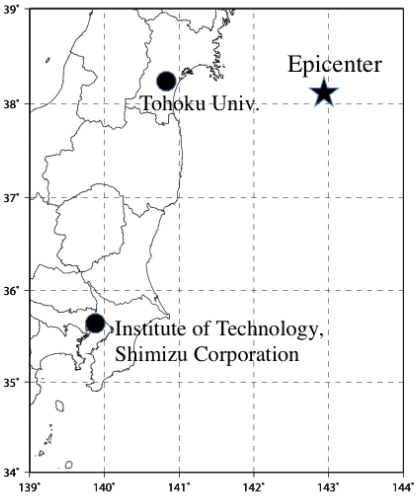
The number of seismic isolated buildings has increased in Japan since the 1995 Kobe Earthquake, and the total number of seismic isolated buildings is said to exceed 2,500, excluding individual seismic isolated houses. In the early implementation of seismic isolation methods, most of the buildings employed ordinary rubber bearings and dampers that were simply installed underneath a structure. The effects of such ordinary seismic isolation methods have been already confirmed through the observed records of past earthquakes in Japan.

Recently, various kinds of new seismic isolation methods have been developed and applied to actual buildings. In Shimizu Corporation's Institute of Technology in Tokyo, there are three different types of seismic isolated buildings, each of which employs a newly developed seismic isolation method: column-top seismic isolation, core-suspended isolation, or partially floating seismic isolation. Each seismic isolated building was installed with earthquake-sensing devices to verify the effects of the applied seismic isolation method.

In addition, Shimizu Corporation and Tohoku University jointly built two three-story reinforced concrete buildings next to each other in the Sendai campus (in Miyagi prefecture): one is a conventional seismically designed building, and the other is a seismic isolated building with six high-damping rubber bearings installed underneath the structure. Although the applied seismic isolation method was an ordinary method, the test buildings stood near the epicenter of the earthquake that occurred at 14:46 on March 11, 2011 off the Pacific coast of Tohoku — hereafter called the 2011 Tohoku–Pacific Earthquake.

Keywords: 2011 Tohoku–Pacific Earthquake, Pacific coast, seismic isolated building, rubber bearing, seismic observation, earthquake response.

(See figure on the right.) Thus it was possible to verify the effects of seismic isolation by directly comparing the earthquake responses in the seismic isolated building with those in the adjacent conventional seismically designed building.



This report describes the effects of the applied seismic isolation methods that were verified through the observed earthquake responses of the above-mentioned four seismic isolated buildings subjected to the 2011 Tohoku–Pacific Earthquake.

2. Overview of the earthquake

The 2011 Tohoku–Pacific Earthquake was an interplate earthquake, occurring on the boundary between the Pacific plate and the Continental plate. Its magnitude was reported as being 9.0, the highest ever recorded in Japan. The scale of this event ranks fourth in the world. The fault plane extended to about 500 km in a North-South direction (length) and about 200 km in an East-West direction (width).

The huge scale of the 2011 Tohoku–Pacific Earthquake produced strong shaking across a broad area. The area with seismic intensity larger than 6− extended to 450 km, and the area with seismic intensity larger than 6+ extended to 300 km. The area with high seismic intensity due to this earthquake was much broader than those in recent destructive inland earthquakes, as shown in Figure 1.

The observed ground motions had a definite feature of a long duration because of the large scale of the fault plane, compared to those of some previous destructive earthquakes, as is shown in Figure 2. The

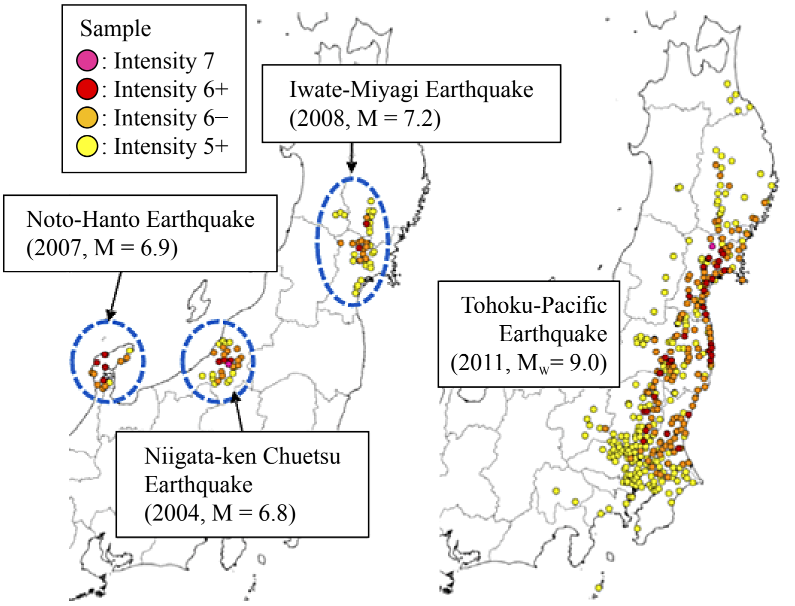


Figure 1. The spatial distribution of the areas with seismic intensity larger than 5+ (in comparison with recent destructive inland earthquakes).

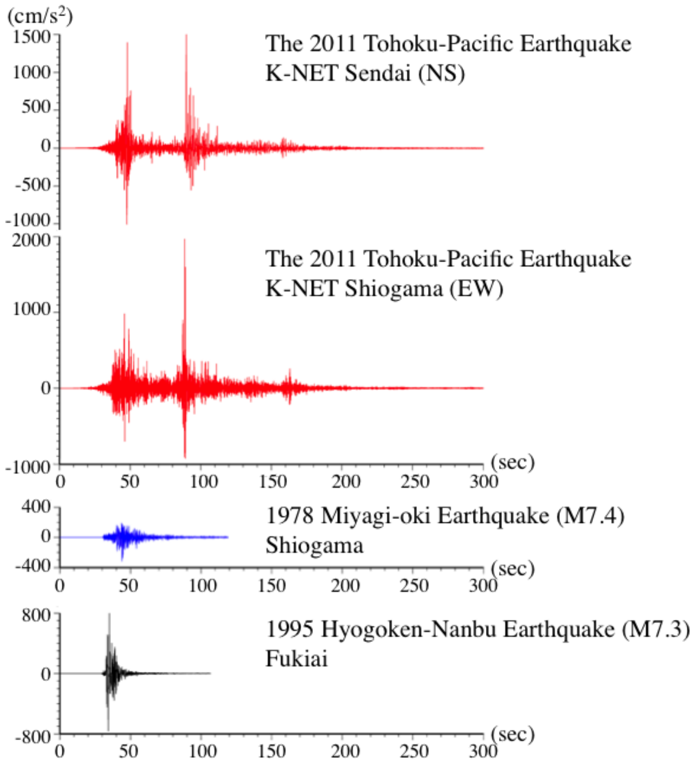


Figure 2. Comparison of observed records at K-NET Sendai and K-NET Shiogama of the 2011 Tohoku–Pacific Earthquake with those from previous destructive earthquakes.

observed ground motions and the response acceleration spectra at Tohoku University and at the institute are shown in Figure 3.

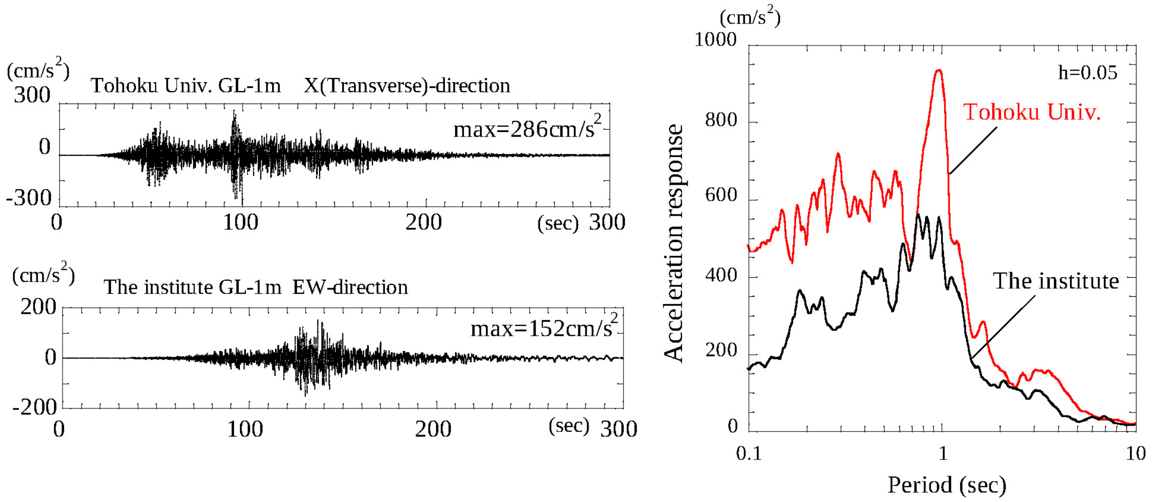


Figure 3. Observed ground motions and response spectra.

3. Overview of the four seismic isolated buildings

Three different types of seismic isolated buildings stand in the grounds of the Shimizu Corporation's Institute of Technology in Tokyo. Each of the three buildings employs a different seismic isolation method, and is installed with earthquake-sensing devices. In addition, Shimizu Corporation and Tohoku University jointly built a test building for seismic isolation within the Sendai campus (in Miyagi prefecture), and have carried out seismographic observations since 1986. The overview of the four seismic isolated buildings is described below.

3.1. ***The Main Building: a column-top seismic isolation system.*** The Main Building in the institute is a 6-story, long-span, seismic isolated structure which utilizes a column-top seismic isolation (CTSI) system [Nakamura et al. 2009]. Table 1 gives the design details of the building. The building uses a large-scale trussed cage structure, the upper part of which is supported on six isolators on independent

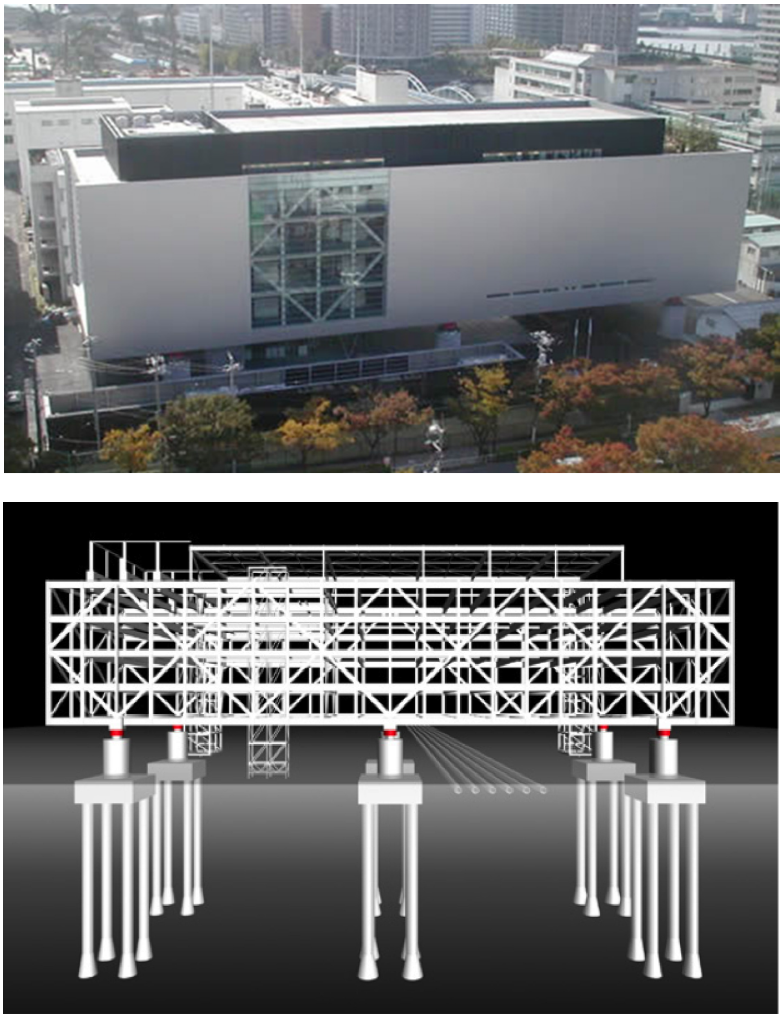


Figure 4. The Main Building (top) and diagram of its structural system.

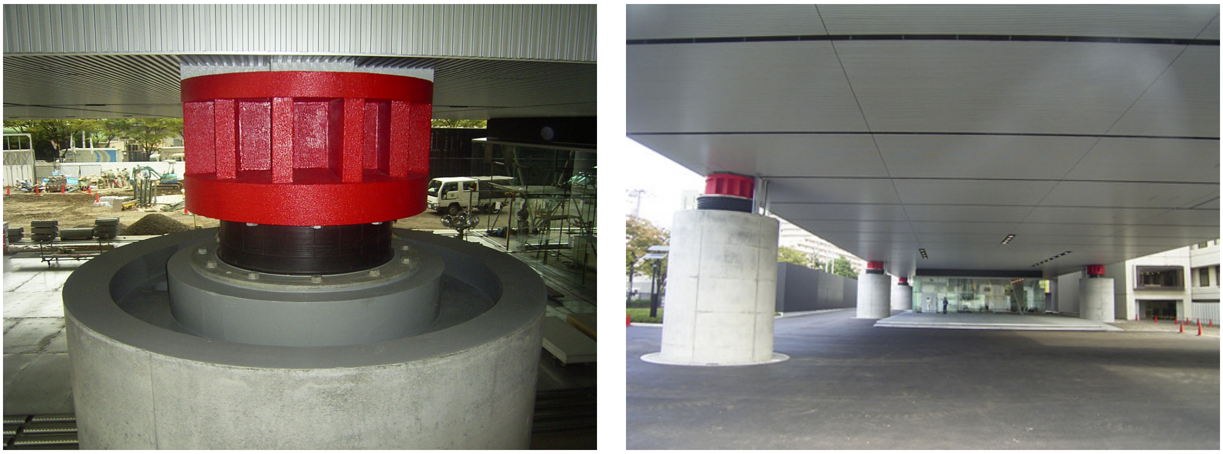


Figure 5. Seismic isolators (lead rubber bearings) on top of first-floor pilotis in the Main Building.

columns, creating an expansive area at ground level, as shown in Figures 4 and 5. Mega-truss frames and rigid frames with bracings are used to provide a large free office space of 80 m × 40 m. Four concrete piles support each isolated column, eliminating the need for footing girders underground.

The seismic isolators are lead rubber bearings of 1,000 mm or 1,100 mm in diameter, as shown in Figure 5, left. Because of the soft soil conditions of the site, the natural period of the seismic isolated structure is designed to be 4.0 s at 200% shear strain level of the isolator. The maximum vertical stress for dead and live loads is an average of 14.1 N/mm^2.

3.2. ***The Safety and Security Center: a core-suspended isolation system.*** A core-suspended isolation (CSI) system consists of a reinforced concrete core on top of which a seismic isolation mechanism composed of a double layer of inclined rubber bearings is installed to create a pendulum isolation mechanism [Nakamura et al. 2011]. The Safety and Security Center, shown in Figure 6, is the first building to utilize the CSI system. Table 2 gives the design details of the building.

Floor area	Total: 9634 m^2, 2nd–5th floors: 1600 m^2 (20 m × 80 m)
Height	Total: 27.6 m; 1st story: 6.8 m; 2nd–5th stories: 4.0 m; penthouse: 4.8 m
Structure	Steel frames and reinforced concrete slabs, total weight: 7000 ton Six lead rubber bearings (LRBs) in total, $G = 0.39$ MPa
Rubber bearings	Three LRBs: diameter: 1000 mm, rubber layers: 6.7 mm × 30 $S1 = 37.3$, $S2 = 5.0$, horizontal stiffness = 20400 kN/m Three LRBs: diameter: 1100 mm, rubber layers: 7.4 mm × 27 $S1 = 37.2$, $S2 = 5.5$, horizontal stiffness = 24800 kN/m Maximum deformation of performance: 450 mm
First mode period (design value)	4.0 s at 200% shear strain level

Table 1. Details of the Main Building.

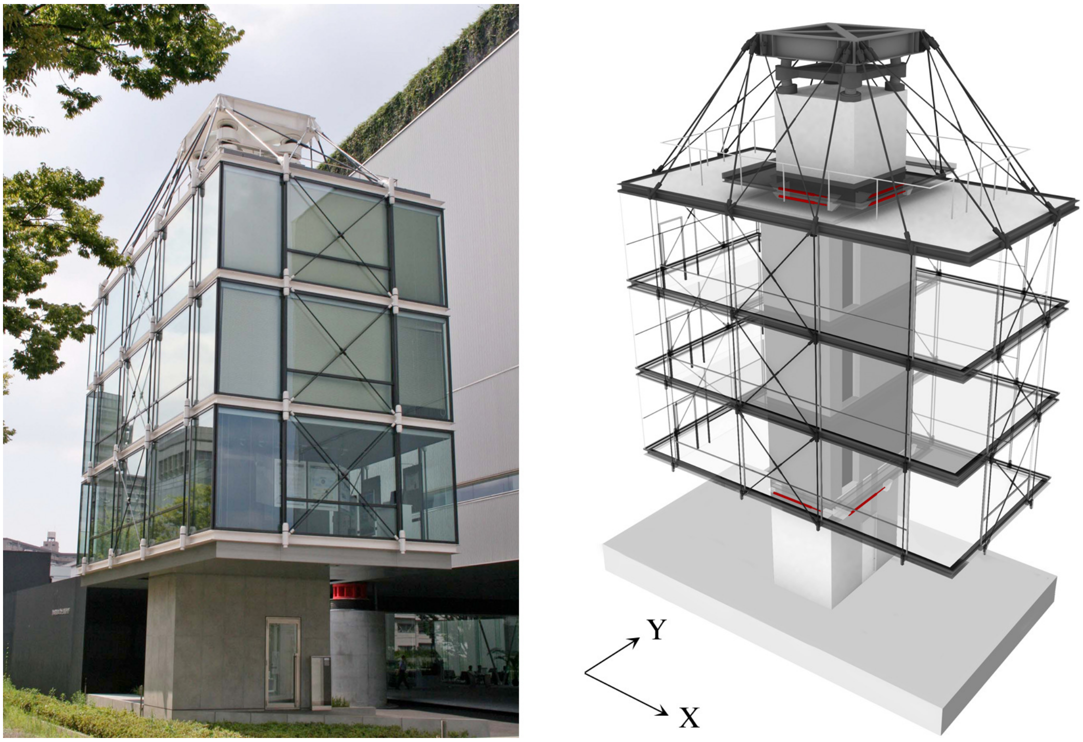


Figure 6. The Safety and Security Center and diagram of its structural system.

The pendulum seismic isolation mechanism for the building consists of two layers each of four inclined rubber bearings, installed at the top of a reinforced concrete core, from which three floors of office structure are suspended by high-strength steel rods, as shown in Figures 6 and 7. Fluid dampers are placed between the core shaft and the suspended office structure to control the motion of the building. The first mode period is designed to be around 5 s in both the X- and Y-directions.

Floor area	Total: 213.65 m^2; 1st floor: 9.05 m^2; 2nd–4th floors: 66.15 m^2; penthouse: 6.15 m^2
Height	Total: 18.75 m; 1st story: 4.15 m; 2nd–4th stories: 3.0 m
Core shaft	Reinforced concrete wall 200 mm thick; 400 mm clearance joint
Suspended structure	Total weight: 180 ton; steel rod column 42 mm diameter
Rubber bearings	Two layers each of four inclined rubber bearings, diameter: 300 mm S1 = 35.7, S2 = 3.11, G = 0.29 MPa, horizontal stiffness = 215 kN/m Maximum deformation of performance: 155 mm
Tilt angles	Lower layer: $\phi_1 = 9.9$ degrees; upper layer: $\phi_2 = 6.6$ degrees
First mode period (design value)	5.08 s in X-dir, 5.14 s in Y-dir.

Table 2. Details of the Safety and Security Center.

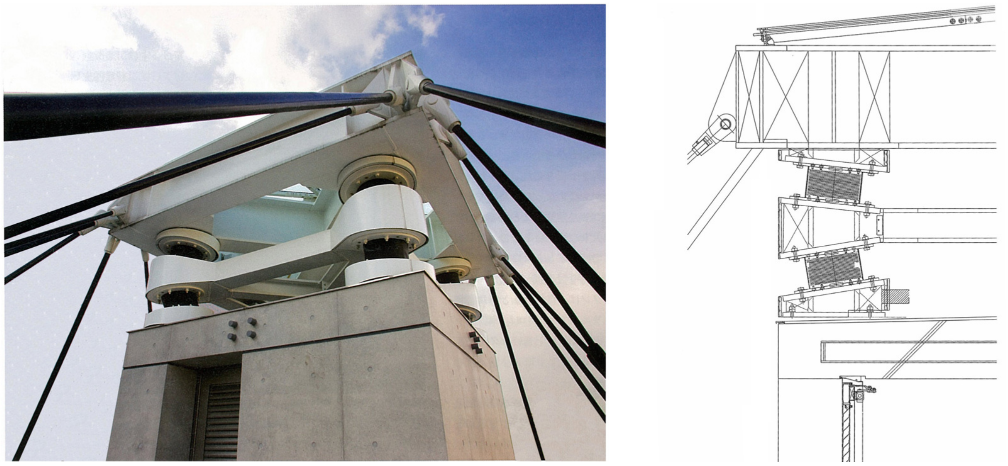


Figure 7. The core-suspended isolation system, comprising two layers, each of four inclined rubber bearings.

3.3. ***The Wind Tunnel Testing Laboratory: a partially floating seismic isolation system.*** A partially floating seismic isolation (PFSI) system utilizes buoyant floatation forces to partially support the gravity weight of the protected structure, along with rubber bearings [Saruta et al. 2007]. In addition, the system utilizes a porous media attached to sides of the basin as a means of damping the structural motion.

The Wind Tunnel Testing Laboratory, shown in Figures 8 and 9, is the first building to utilize the PFSI

Figure 8. The Wind Tunnel Testing Laboratory.

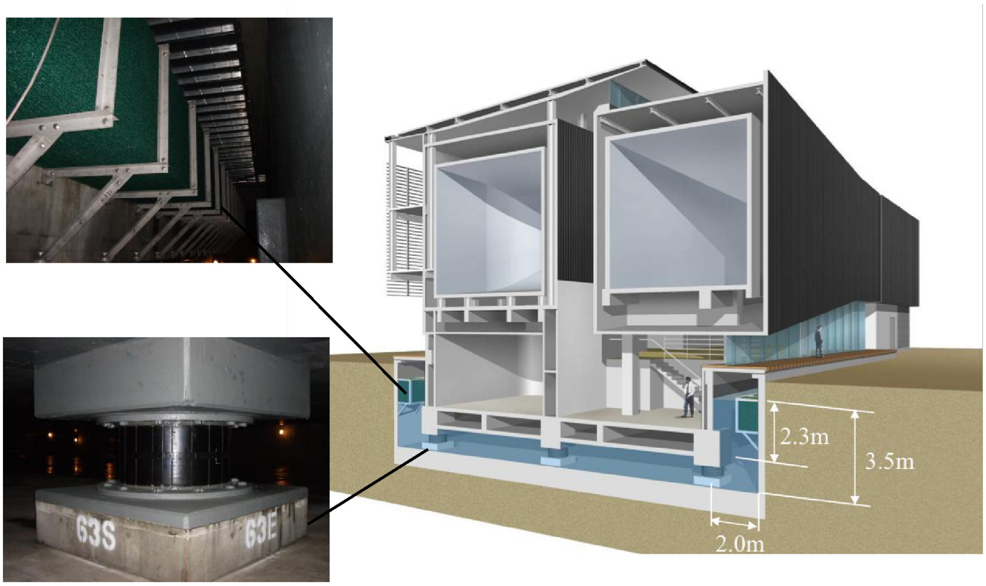


Figure 9. A cross section of and the structural system of the partially floating seismic isolation system.

system. The basement, as shown in Figure 9, is of 2.3 m draft, and half of the weight of the structure is supported by buoyancy. Table 3 gives the design details of the building. The natural period of the seismic isolated structure is designed to be 4.1 s.

Floor area	Total: 1253 m^2 (3 stories above the ground, 1 underground floor)
Height	Total: 17.2 m (12.7 m above the ground, 4.5 m underground)
Structure	Reinforced concrete (partly, steel structure)
Weight	Total weight: 2900 ton
Draft of structure	2.3 m (Half of weight is supported by buoyancy)
Rubber bearings	14 high-damping rubber bearings (HDRBs) in total, G = 0.39 MPa, covered by lining rubber including steel flange plates (Figure 9, lower left) 7 HDRBs: diameter: 650 mm, rubber layers: 4.4 mm × 45 S1 = 36.1, S2 = 3.28, horizontal stiffness = 3230 kN/m maximum deformation of performance: 461 mm 7 HDRBs: diameter: 700 mm, rubber layers: 4.7 mm × 43 S1 = 36.4, S2 = 3.46, horizontal stiffness = 3670 kN/m maximum deformation of performance: 485 mm
Reservoir	Area: 830 m^2, depth: 4.5 m, volume of water: 1540 ton
First mode period (design value)	4.1 s

Table 3. Details of the Wind Tunnel Testing Laboratory.

3.4. ***The test buildings in Tohoku University.*** Shimizu Corporation and Tohoku University jointly built two adjacent three-story reinforced concrete buildings in the Sendai campus (Miyagi prefecture) as shown in Figure 10: one is a conventional seismically designed building, and the other is a seismic isolated building with six high-damping rubber bearings installed underneath the structure [Saruta et al. 1989]. Table 4 gives the design details of the test buildings.

Figure 10. Test buildings at Tohoku University. Left: conventional seismically designed building; right: seismic isolated building.

Floor area	Each building	Total: 180 m^2; 1st–3rd floors: 60 m^2 (6 m × 10 m)
Height	Each building	Total: 9.9 m; 1st–3rd stories: 3.3 m
Structure	Each building	Reinforced concrete
Weight	Conventional building	Total weight: 176 ton
	Seismic isolated building	Total weight: 255 ton
Rubber bearings	Seismic isolated building	6 HDRBs: diameter: 435 mm rubber layers: 6.7 mm × 18 S1 = 16.2, S2 = 3.6 horizontal stiffness = 627 kN/m
First mode period (design value)	Conventional building	0.3 s
	Seismic isolated building	1.6 s (at deformation of bearing = 8 cm)

Table 4. Details of the test buildings in Tohoku University.

4. Observed earthquake responses of the four seismic isolated buildings

A structural health monitoring (SHM) system was implemented into the four seismic isolated buildings to detect their seismic performance [Okada et al. 2009]. The effects of applied seismic isolation methods were verified through the observed earthquake responses of the four seismic isolated buildings subjected to the 2011 Tohoku–Pacific Earthquake.

4.1. ***The Main Building.*** Figure 11 shows the maximum acceleration responses of the Main Building when subjected to the 2011 Tohoku–Pacific Earthquake. Observed acceleration waves on the ground and 6th floors are shown in Figure 12. The maximum accelerations on the floors of the seismic isolated structure were story-wise almost uniform, and reduced to about half compared to those on the ground.

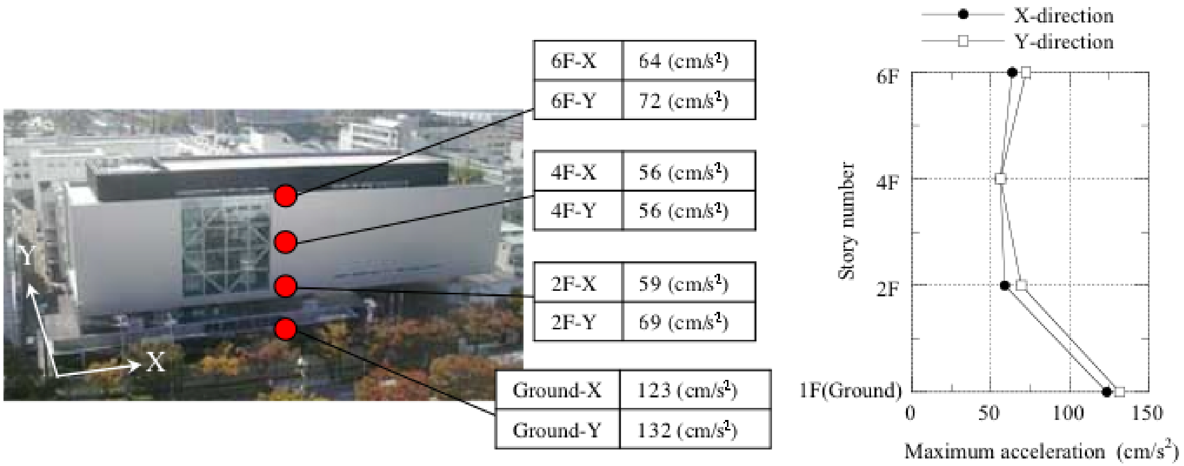


Figure 11. Maximum responses of the Main Building.

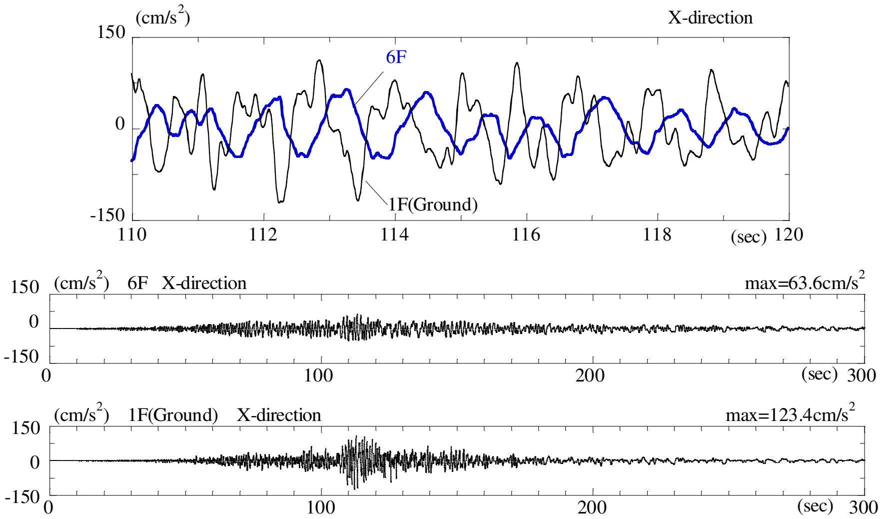


Figure 12. Observed acceleration waves on the ground and on the 6th floor of the Main Building.

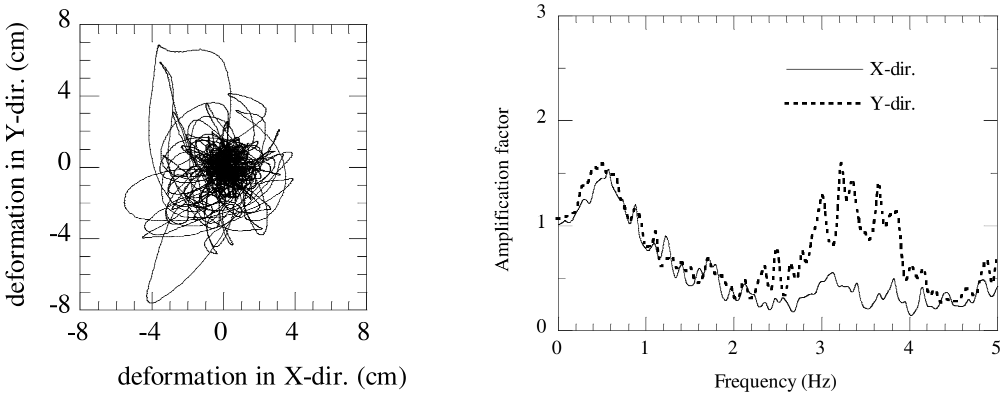
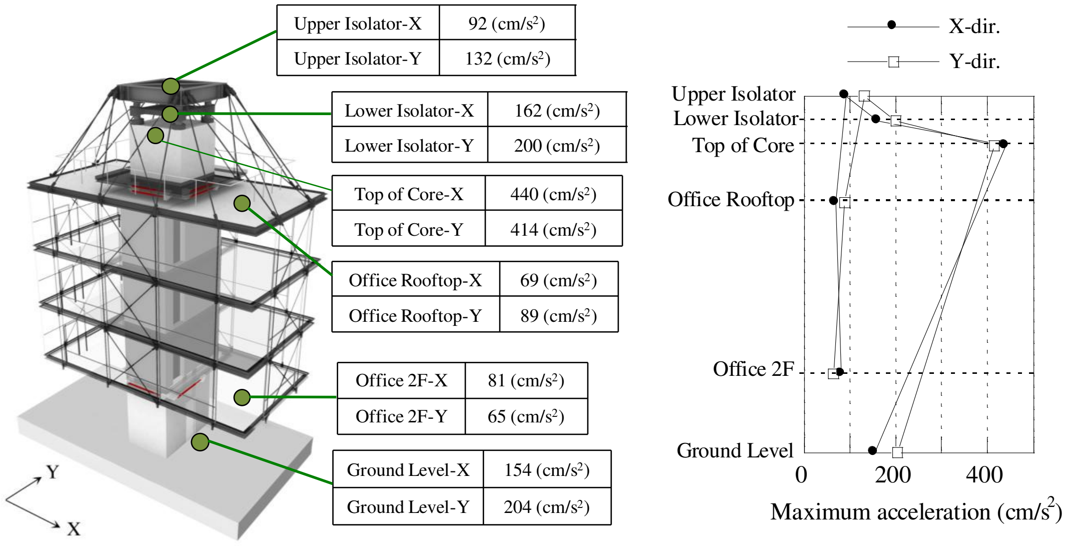


Figure 13. Main Building observations: locus of the horizontal deformation of an LRB (left) and transfer function of the acceleration (6th floor relative to ground floor).

The locus of the horizontal deformation of a lead rubber bearing is shown in Figure 13, left. The maximum displacement of the rubber bearing was 8.6 cm, which was much less than the maximum deformation of performance, which was 45 cm.

Figure 13, right, shows the transfer functions of the observed accelerations on the 6th floor relative to those on the ground. The transfer function indicates that the fundamental natural period of the seismic isolated structure was about 2 s, which is shorter than the designed first-mode period.

4.2. *The Safety and Security Center.* Figure 14 shows the maximum acceleration responses of the Safety and Security Center when subjected to the 2011 Tohoku–Pacific Earthquake. Though the acceleration responses were amplified at the top of the core structure, the CSI system reduced them and the maximum



Upper Isolator-X	92 (cm/s^2)
Upper Isolator-Y	132 (cm/s^2)
Lower Isolator-X	162 (cm/s^2)
Lower Isolator-Y	200 (cm/s^2)
Top of Core-X	440 (cm/s^2)
Top of Core-Y	414 (cm/s^2)
Office Rooftop-X	69 (cm/s^2)
Office Rooftop-Y	89 (cm/s^2)
Office 2F-X	81 (cm/s^2)
Office 2F-Y	65 (cm/s^2)
Ground Level-X	154 (cm/s^2)
Ground Level-Y	204 (cm/s^2)

Figure 14. Maximum responses of the Safety and Security Center.

accelerations on the floors in the hung structure were reduced to about half in the X-direction, and to about one third in the Y-direction, compared to those on the ground, respectively. Observed acceleration waves on the ground level and on the 2nd floor in the office are shown in Figure 15.

Figure 16, left, shows the locus of the horizontal relative displacement between the core structure and the 2nd floor in the office. The maximum relative displacement was about 8 cm, much less than the clearance of 40 cm. Figure 16, right, shows the transfer functions of the observed accelerations in

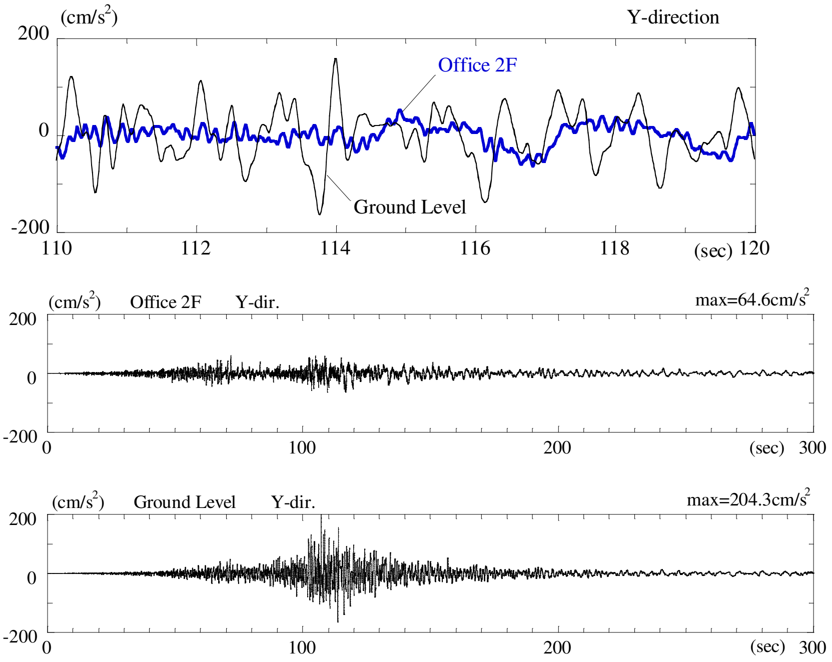


Figure 15. Observed acceleration waves on the ground level and in an office on the 2nd floor of the Safety and Security Center.

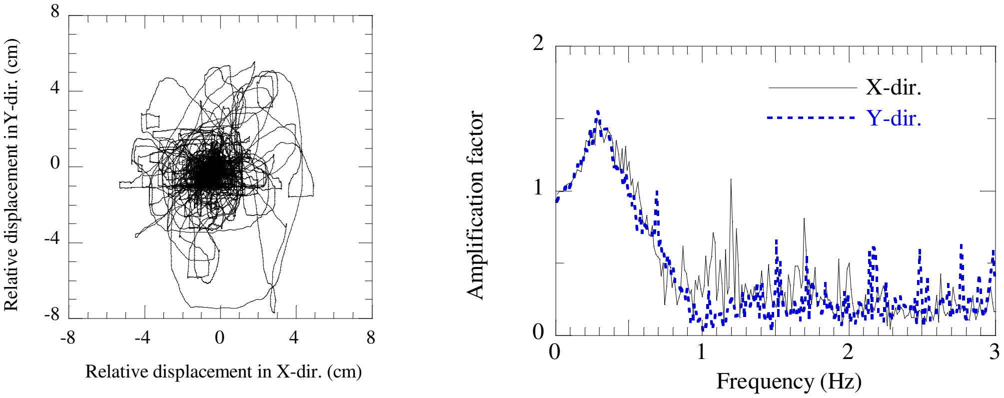


Figure 16. Safety and Security Center: Relative displacement between a 2nd floor office and the core structure (left), and acceleration transfer function for 2nd floor office on relative to ground level.

the 2nd floor office relative to those on the ground level, which indicate that the fundamental natural period of the hung structure was 3.6 s (0.28 Hz) in the X-direction, and 3.4 s (0.29 Hz) in the Y-direction, respectively. These values are shorter than the designed first-mode periods.

4.3. ***The Wind Tunnel Testing Laboratory.*** Figure 17 shows the maximum acceleration responses of the Wind Tunnel Testing Laboratory when subjected to the 2011 Tohoku–Pacific Earthquake. On the roof, the acceleration response in the Y-direction was amplified because the top part of the building is partially made of steel. The maximum accelerations in the 1st basement level and on the 2nd floor of the structure were reduced to about half in both directions, compared to those at the base of the pit.

Figure 18, left, plots the locus of the horizontal deformation of a rubber bearing. The maximum displacement of the rubber bearing was 7.8 cm, much less than the maximum deformation of performance,

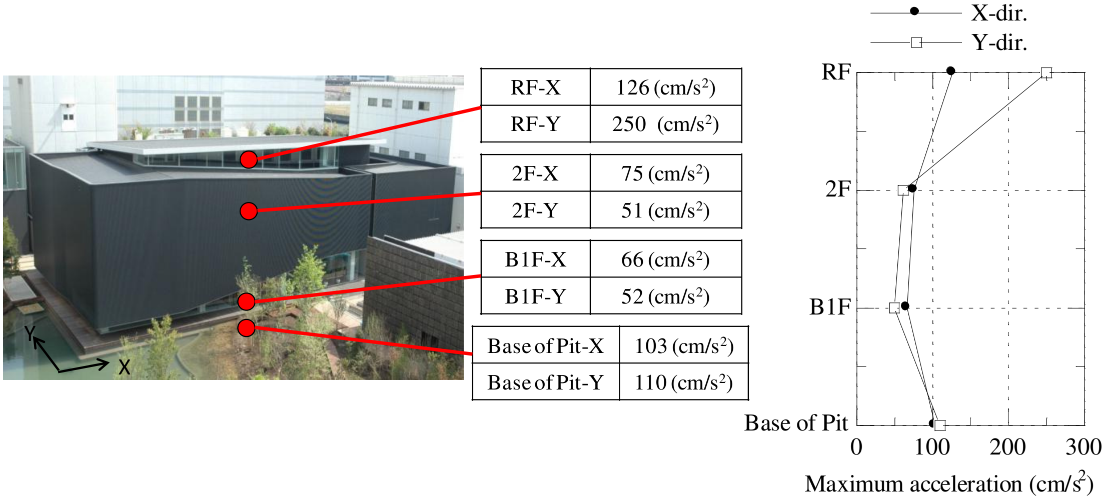


Figure 17. Maximum responses of the Wind Tunnel Testing Laboratory.

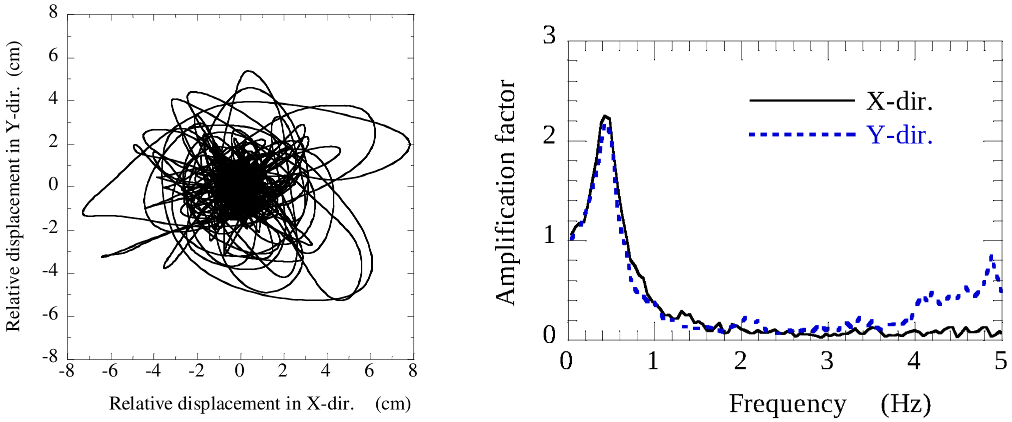


Figure 18. Wind Tunnel Testing Laboratory: locus of the horizontal deformation of a rubber bearing (left) and acceleration Transfer functions for 1st basement level versus base of the pit.

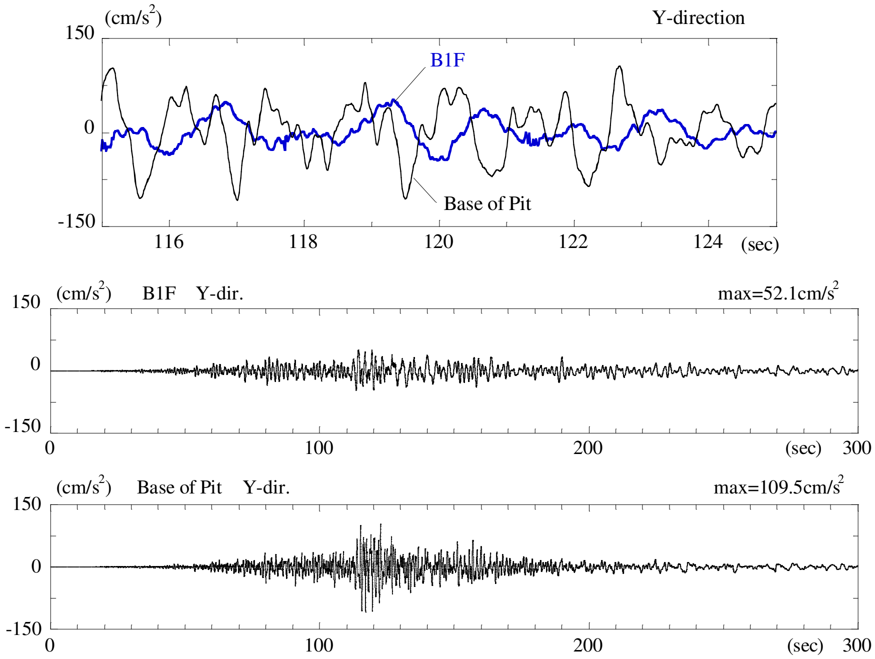


Figure 19. Observed acceleration waves at the base of the pit and on the 1st basement level in the Wind Tunnel Testing Laboratory.

which was 46 cm. Figure 18, right, shows the transfer function of the observed accelerations on the 1st basement level to those at the base of the pit, which indicates that the fundamental natural period of the isolated structure was 2 s (0.5 Hz). This value is shorter than the designed first-mode period. The observed acceleration waves at the base of the pit and on the 1st basement level are shown in Figure 19.

4.4. ***The test buildings in Tohoku University.*** Maximum acceleration responses of the two test buildings when subjected to the 2011 Tohoku–Pacific Earthquake are shown in Figures 20 and 21. In the seismic

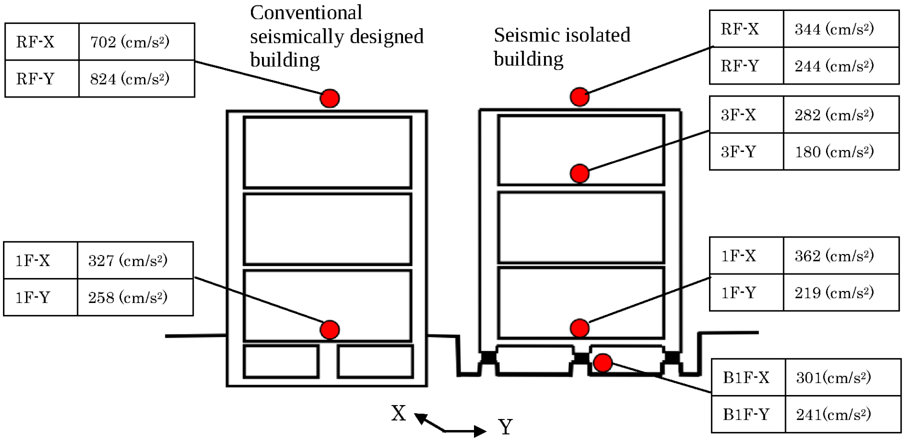


Figure 20. Maximum responses of the test buildings in Tohoku University.

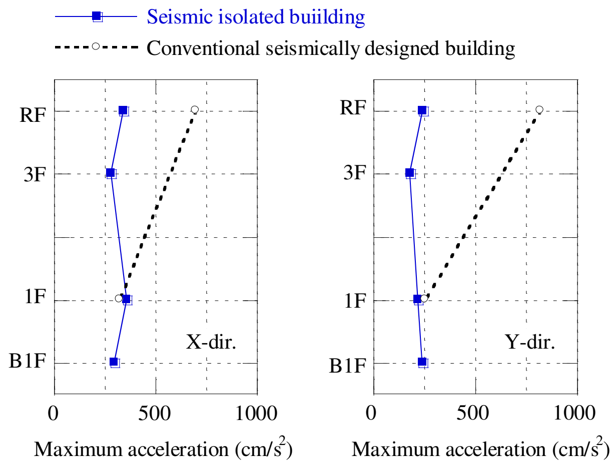


Figure 21. Maximum responses of the test buildings in Tohoku University (continued).

isolated building, the observed accelerations on the roof were reduced to about half in the X-direction, and to about one third in the Y-direction, respectively, compared to those in the adjacent conventional seismically designed building.

Figures 22 and 23 show the observed acceleration waves in the test buildings. In Figure 23, the observed acceleration wave on the roof of the seismic isolated building is expanded and overlaid onto that of the conventional seismically designed building, clearly demonstrating the differences in the earthquake responses of the two test buildings.

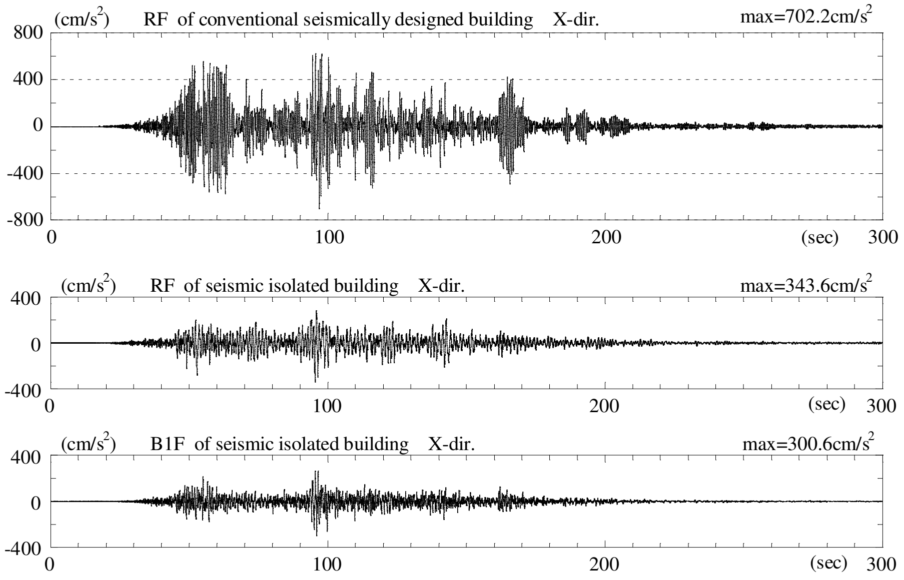


Figure 22. Observed acceleration waves in the conventional seismically designed building (RF) and in the seismic isolated building (1st basement level and RF).

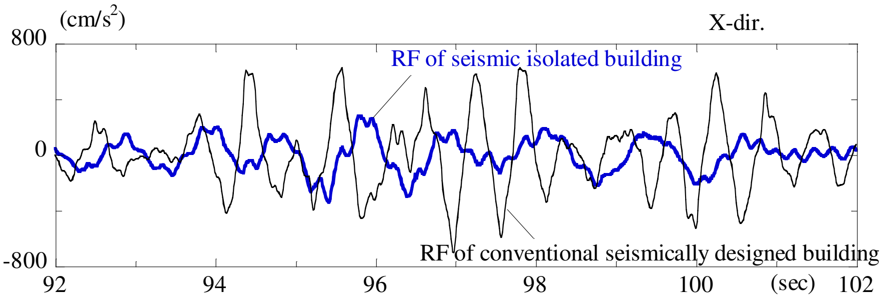


Figure 23. Observed acceleration waves on the RF in the two test buildings in Tohoku University.

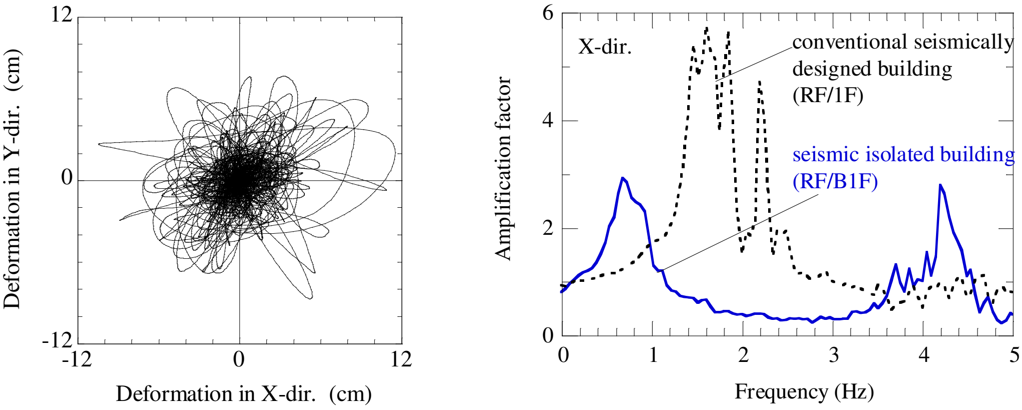


Figure 24. Left: locus of the horizontal deformation of the rubber bearing of the seismic isolated building in Tohoku University. Right: transfer functions of the observed accelerations (RF /1F, RF/B1F) of the test buildings in Tohoku University.

The locus of the horizontal deformation of a rubber bearing is shown in Figure 24, left. The maximum displacement of the rubber bearing was 11.5 cm, which was less than the maximum deformation of performance, which was 36 cm.

Figure 24, right, shows the transfer function of the observed accelerations on the roof to the 1st basement of the seismic isolated building, along with the one of the conventional seismically designed building. The fundamental natural period of the seismic isolated building was 1.6 s (0.6 Hz) in the X-direction, while that of the conventional seismically designed building was 0.6 s (1.6 Hz).

5. Vertical responses of the seismic isolated structures

The applied seismic isolation methods were installed with the intent of decreasing the horizontal earthquake responses of the structure, and have been proven to be quite effective in reducing the horizontal acceleration responses through the observed records of the 2011 Tohoku–Pacific Earthquake, as described above. Here, we discuss whether seismic isolation methods are also effective in reducing vertical responses.

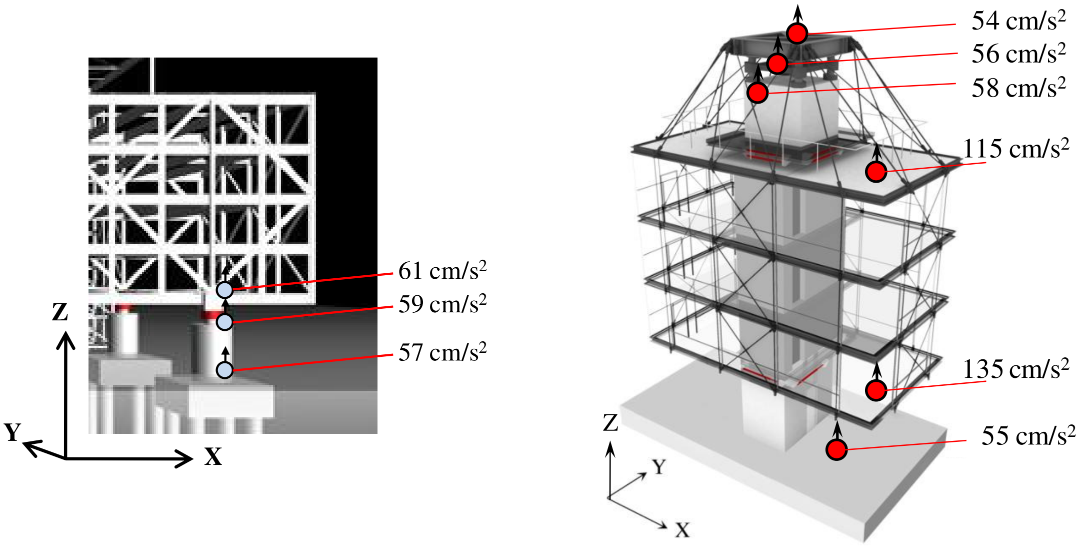


Figure 25. Maximum acceleration responses in the vertical direction of the Main Building (left) and of the Safety and Security Center (right).

Seismographs for the vertical direction were installed in the Main Building and the Safety and Security Center. Figure 25 shows the maximum acceleration responses in the vertical direction of the Main Building and of the Safety and Security Center. In the Main Building, as shown in Figure 25, left, the value of the maximum acceleration above the isolator was almost same as that below the isolator. In the Safety and Security Center, as shown in Figure 25, right, the values of the maximum acceleration response were almost constant from the ground level to the top of the core structure, while those for the hung office were even amplified to two to three times as much as that on the ground level.

These results illustrate that seismic isolation methods are not effective in reducing the vertical responses of a structure. The amplification of the vertical responses in a building may need to be taken into consideration, especially in long-span structures and in hung structures.

6. Conclusions

The 2011 Tohoku–Pacific Earthquake that occurred on March 11, 2011 caused devastating damage to the northeast Pacific coast region of Japan. The magnitude was reported as being 9.0, the highest magnitude ever recorded in Japan. The huge scale of this earthquake produced strong shaking across a broad area. The observed ground motions had a definite feature of a long duration because of the large scale of the fault plane.

Three different types of seismic isolated buildings stand in the Shimizu Corporation's Institute of Technology in Tokyo. Each of the three buildings employs a different seismic isolation method: the Main Building by column-top seismic isolation (CTSI) system, the Safety and Security Center by core-suspended isolation (CSI) system, and the Wind Tunnel Testing Laboratory by partially floating seismic isolation (PFSI) system. Shimizu Corporation and Tohoku University jointly built a test building for seismic isolation in the Sendai campus (in Miyagi prefecture), which was near the epicenter of the 2011 Tohoku–Pacific Earthquake.

The effects of applied seismic isolation methods were verified through the observed earthquake responses of the four seismic isolated buildings subjected to the 2011 Tohoku–Pacific Earthquake. In each of the three seismic isolated buildings in the institute, the observed accelerations on the floors were reduced to about half compared to those on the ground. In the test seismic isolated building in Tohoku University, the observed accelerations on the roof were reduced to about one third compared to those in the adjacent conventional seismically designed building.

The observed vertical responses in the seismic isolated buildings illustrate that seismic isolation methods are not effective in reducing the vertical responses of the structure. The amplification of vertical responses in a building may need to be taken into consideration, especially in the long-span structures and in hung structures.

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