Seismic Isolation Retrofit of Susono City Hall Situated above Lava Tubes

H.Nakamura, T.Ninomiya & T.Sakaguchi
Housing and Construction Inspection Section, Susono City Office

Y.Nakano, K.Konagai, M.Takayama, Y.Hisada, M.Seki, T.Ota, Y.Yamazaki, S.Mochizuki, T.Yanagi, T.Ohishi & A.Takahashi
The Special Committee on Seismic Isolation Retrofit of the Susono City Hall

SUMMARY:
The Susono City conducted a seismic retrofit for its city hall by implementing seismic isolation system so that the retrofitted building would function as a disaster management center in response to a large earthquake. The building rests on a firm lava bed with an inclusion of two-level lava tubes, which were found by chance in 1975 when the building was originally constructed. In pursuing the seismic retrofit project for implementing seismic isolation system, which requires completely stable flat foundation, the upper lava tube was filled up with foamed concrete called air-milk which can be consolidated to exhibit substantial strength. After filling up the lava tube, the building was lifted upon 55 rubber bearings and 5 oil dampers, which were placed in the mid-story of its basement. The micro-tremors observed before and after the retrofit show that filling up the lava tube did not affect substantially the dynamic features of the building, and the period of the building became longer by about 0.10-0.14s after installation of seismic isolators.

Keywords: seismic isolation retrofit, lava tube, air-milk, micro-tremor observation

1. INTRODUCTION

The city of Susono, Shizuoka Prefecture, being located about 100km to the west of Tokyo, is a small city of auto industry spreading over the foot of Mt. Fuji, the Japan's highest peak with an altitude of 3,776 m. Its City Hall for about 250 officers is a 5 story reinforced concrete building with a single story basement and the total floor area of 6,435.25m^2.

The building is resting on a firm lava bed which had spread in the path of least resistance and solidified when Mt. Fuji was very active approximately 10,000 to 14,000 years ago. When the city hall was originally constructed in 1975, two-level lava tubes, which had been formed as conduits when outer layers of the lava hardened, while the interior were molten, were found underneath the building.

Being located near boundaries of major three tectonic plates, the area has been under a threat of a possible scenario Tokai inter-plate earthquake, and the city of Susono decided to perform a seismic retrofit of the building, which can be a disaster management center in response to a big earthquake. The city then set up a Special Committee for this retrofitting project composed of experts on geotechnical engineering and earthquake engineering. Based on the recommendations by the committee, the city decided to install seismic isolation system ensuring the stability of its foundation by filling up the lava tube with foamed concrete called air-milk, which can be consolidated to exhibit substantial strength.

In addition, the micro-tremor observations before and after the retrofit were carried out to examine the change of the dynamic features of the foundation-structure system.

This paper describes the design concept as well as practical solutions for the seismic retrofit of the city hall immediately above the lava tubes together with micro-tremor observation results before and after the retrofit.

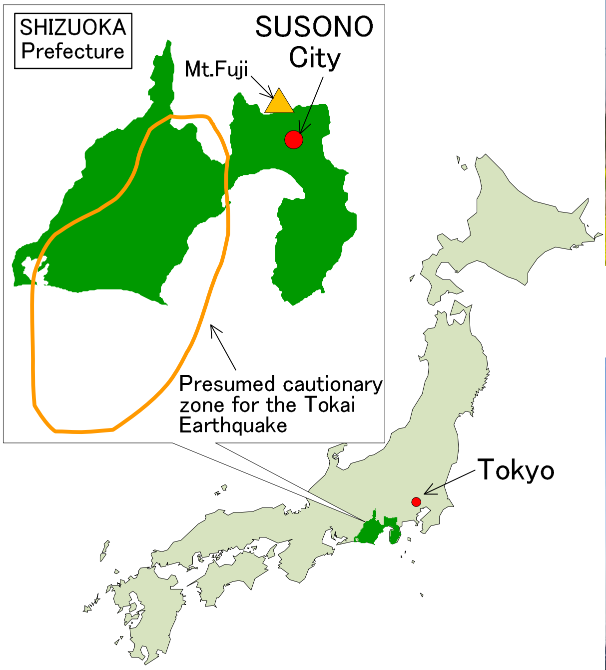


Figure 1. Location of the city of Susono

Photo 1. Mt. Fuji

Photo 2. Susono City Hall

2. LAVA TUBE

2.1. Formation of Lava Tube

Numerous lava tubes exist underground over the entire foot of Mt. Fuji. Susono City and its neighboring cities are no exception. Two lava tubes were found immediately beneath the Susono City Hall by chance in 1975 when the city hall was being constructed. Mt. Fiji is considered to have been in active eruption approximately 10,000 years ago such that upwelling lava through the magma tube spilled over the lip of the volcano, and flows of lava ran down the side of the Mt Fuji. These flows included the one that flowed through Susono to Mishima. The outer surface of this lava cooled fastest, while molten lava continued to flow through the resulting tubes.

2.2. Original Measures to Cope with Lava Tube

The boring survey was carried out at 37 points during the construction period of the city hall building in 1975 to get the whole picture of the lava tube. The survey revealed that there were two tubes at different levels at around 7.8 to 10.2 m and around 12 m beneath the ground surface. The upper lava tube was estimated to be about 78 m long and 7 to 15 wide in EW and NS directions, respectively, and about 0.4 - 1.7 m high.

As there was no alternative site, the city had no option but to ensure stability of the foundation of the city hall by driving steel piles deep into the basal rock. It was fortunate that no strong earthquake has occurred in the city since the completion of the city hall in 1977, and no uneven settlement of the City Hall was observed in the inspection in 2005.

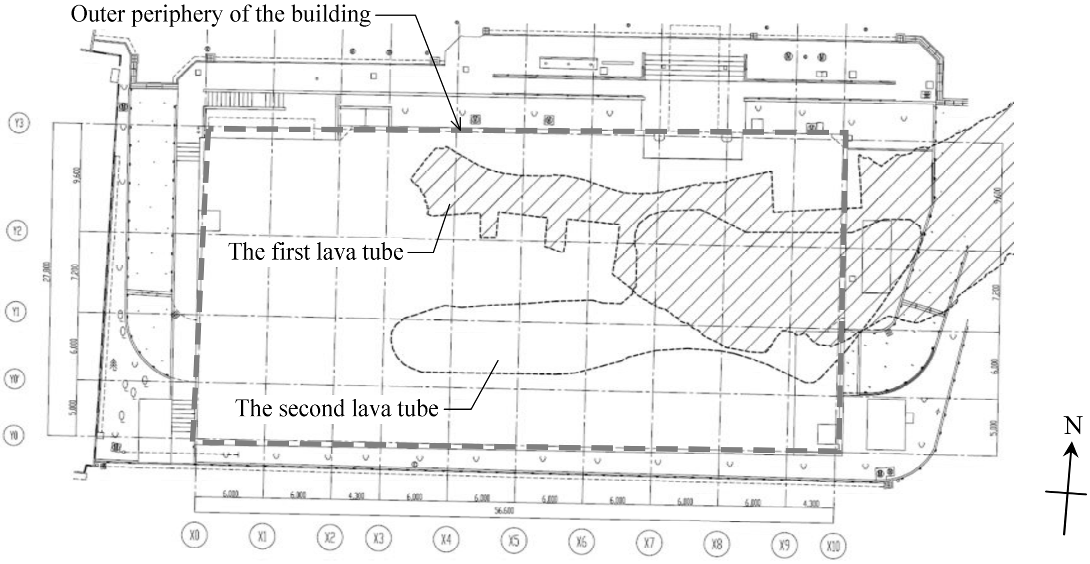


Figure 2. Lava tubes beneath Susono City Hall (Plan)

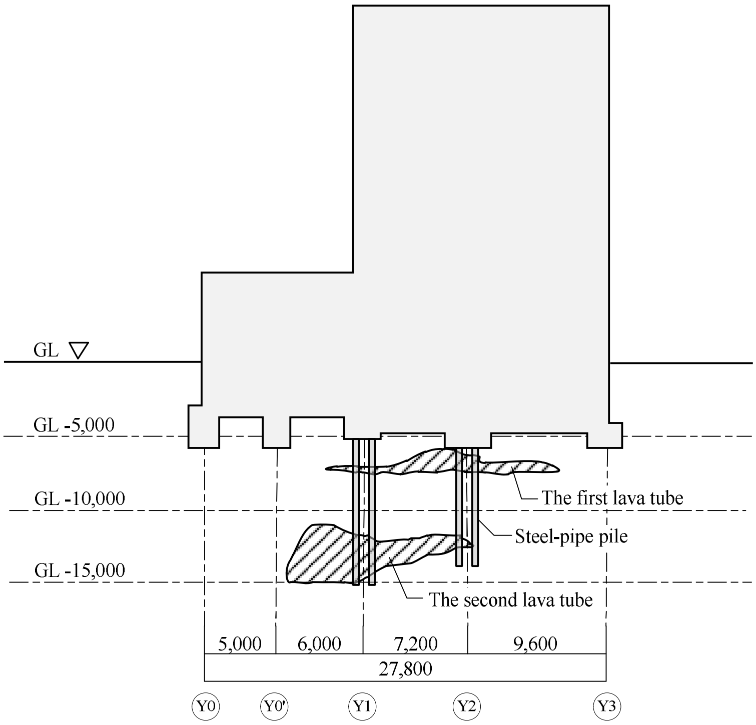


Figure 3. Lava tubes beneath Susono City Hall (Cross-section)

Photo 3. Steel-pipe piles for the city hall driven through lava tubes

3. SEISMIC RETROFIT PROJECT

3.1. Seismic Performance of Original Susono City Hall

The Susono City gained congressional acceptance in 2007 for pursuing seismic retrofit for all municipal buildings including the Susono City Hall until March 2016. The seismic evaluation of the original Susono City Hall was carried out in 2005 based upon the Manual for Seismic Evaluation and Seismic Retrofit of Existing Buildings in Shizuoka Prefecture, Shizuoka Association of Architectural Firms (SAAF). This Manual for buildings in Shizuoka is fully compliant with the Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings, the Japan Building Disaster Prevention Association (JBDPA). According to the standard, the seismic performance index of a building is expressed with *Is*, seismic index of structure, and in the manual *Is*-index is also used to describe seismic performance. The manual claims that *Is*-index should be higher than E_T, the criterion of seismic demand of a building.

Shizuoka Prefecture defines E_T-index as the criterion for the seismic capacity required in the scenario Tokai Earthquake. The index varies with stories, geological conditions, landforms and for building uses. In the case of the Susono City Hall, E_T-index was calculated to be 1.13. If the *Is* values of all the building stories are higher than 1.13, the building can be confirmed to be safe. If not, the building safety is in doubt. Additionally the manual and the standard recommend the strength index $C_{TU} * S_D$ larger than 0.3. Table 1. shows the evaluated safety indices for the city hall. *Is* values for most stories were less than the E_T value of 1.13. Therefore the city decided to commence as soon as possible the seismic retrofit project for the Susono City Hall.

Table 1. Seismic performance indices

Story	East-West direction			North-South direction		
	Is	$C_{TU} * S_D$	Judgment	*Is*	$C_{TU} * S_D$	Judgment
5	0.90	0.55	NG	2.08	2.10	OK
4	0.76	0.77	NG	1.30	1.31	OK
3	0.73	0.74	NG	1.12	1.13	NG
2	0.64 (min.)	0.65	NG	0.93 (min.)	0.93	NG
1	0.66	0.66	NG	0.97	0.97	NG
B1	1.38	1.39	OK	1.14	1.15	OK

3.2. Special Committee on Seismic Retrofit of Susono City Hall

In pursuing the seismic retrofit project for implementing seismic isolation system, which requires completely stable flat foundation, the lava tube was the major concern, and the city organized a special committee of experts on geotechnical engineering and seismic engineering. The committee, as a third party body, evaluated the stability of foundation resting on the lava with an inclusion of lava tubes, and examined some feasible measures. The city proceeded with the project paying close attention to the results of the committee's evaluation and examination.

3.3. Design Concept of Seismic Retrofit

The objective of seismic retrofit is to secure the safety of visitors and staffs in the city hall and maintain the function of the city hall as a disaster management center. Furthermore, it was mandatory for the retrofitting project to be conducted without interference with regular routine functions of the city hall. The required seismic performance of the building shall be such that the structure would not need any repair works after experiencing level 1 and level 2 earthquakes. The level 1 earthquake is the middle-scale earthquake, which a building encounters several times during its lifetime. The level 2 earthquake is the large-scale earthquake which a building encounters once during its lifetime. Table 2 shows the design criteria for the two level earthquakes. Table 3. shows the results of seismic response analysis.

Table 2. Design criteria

		Level 1 earthquake	Level 2 earthquake
Required seismic performance of building		Primary structure undamaged without repair work	
Objective performances	Superstructure	Stay bellow allowable lateral stress, Max. deflection : 1/1000	Stay bellow elastic strength, Max. deflection : 1/500, Max. acceleration : 300gal
	Isolation device	Stay bellow stable displacement (shear strain γ : 200%), No tension	Stay bellow design displacement (shear strain γ : 300%), Limit tension strength : $-1.0 N/mm^2$
		Allowable lateral displacement : 32cm	Allowable lateral displacement : 48cm
	Substructure	Stay bellow allowable lateral stress	
	Foundation	Stay bellow allowable lateral stress	

Table 3. Results of seismic response analysis

	Level 1 earthquake	Level 2 earthquake
Superstructure	Max. stress : 1.2 times less than allowable lateral stress, Max. deflection : 1/2334 (X), 1/14996 (Y)	Max. shear stress : less than elastic strength, Max. deflection : 1/612 (X), 1/4006 (Y), Max. acc. : 281.9gal (X), 272.4gal (Y)
Isolation device	Max. displacement : 7.1cm (less than stable displacement), No tension stress	Max. displacement : 44.3cm (less than design displacement), Max. tension stress : $-0.9 N/mm^2$
Substructure	Max. stress : 1.15 times less than allowable lateral stress	
Foundation	Max. stress : 1.20 times less than allowable lateral stress	

3.4. Lava Tube Filled Up with Air-milk

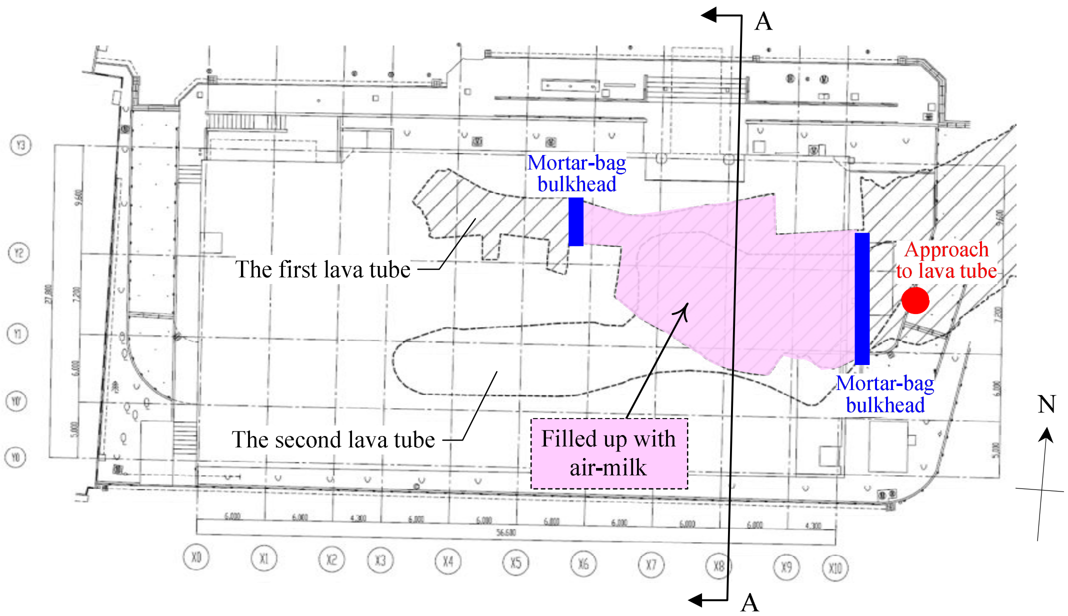
It was decided that the hollow of the upper level lava tube, namely the first lava tube, would be filled up with foamed concrete prior to the seismic isolation retrofit, to prevent the collapse of the tube and to avoid the stress concentration around the jagged surface of the lava tube due to both vertical dead load and lateral seismic forces.

The foamed concrete, called air-milk, is the mixture of cement, water and air-foam and can be consolidated to exhibit substantial strength fitting the irregular surface of the interior of the lava tube. Its substances are hard to be segregated and atoxic, thus do not harm environment.

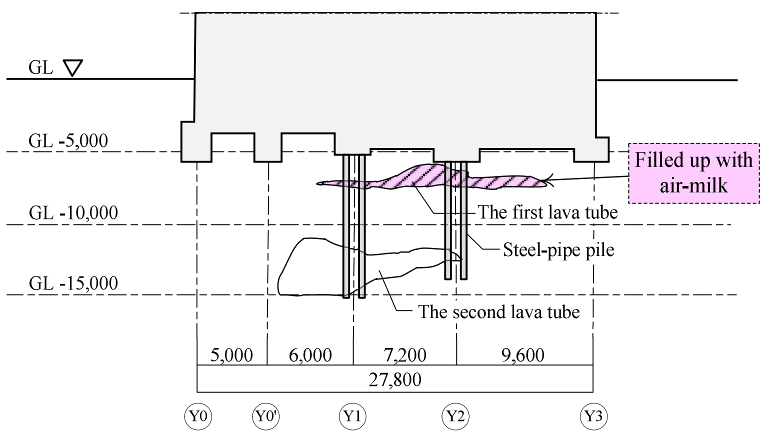
Stress distribution in the interior of the lava bed was analyzed with the two dimensional finite element method, and the stability of the lava bed with its tube filled up was examined. The analysis showed that the lava bed had safety factors 3.0 and 1.5 for static and dynamic loads.

The lower lava tube was left as it was because it was found deep enough not to affect the stability of the foundation. Moreover it was expected for the lower tube to serve as a drainage channel.

For filling up the first lava tube, there installed in the lava tube enclosed with mortal-bag bulkheads 9 pipes to inject air-milk, 8 air-pressure release pipes and 9 contact sensors which are pairs of electric wires at crowns of the tube to detect if the air-milk touched the crowns. It took three-days to inject total $234m^3$ air-milk in the enclosed lava tube In this process, the filling progress was monitored through one existing access pit to the tube, signals from mortar contact sensors and mortar leaks through the air-pressure release pipes (Table 4).



(1) Plan



(2) A-A Section

Figure 4. First lava tube filled up with air-milk

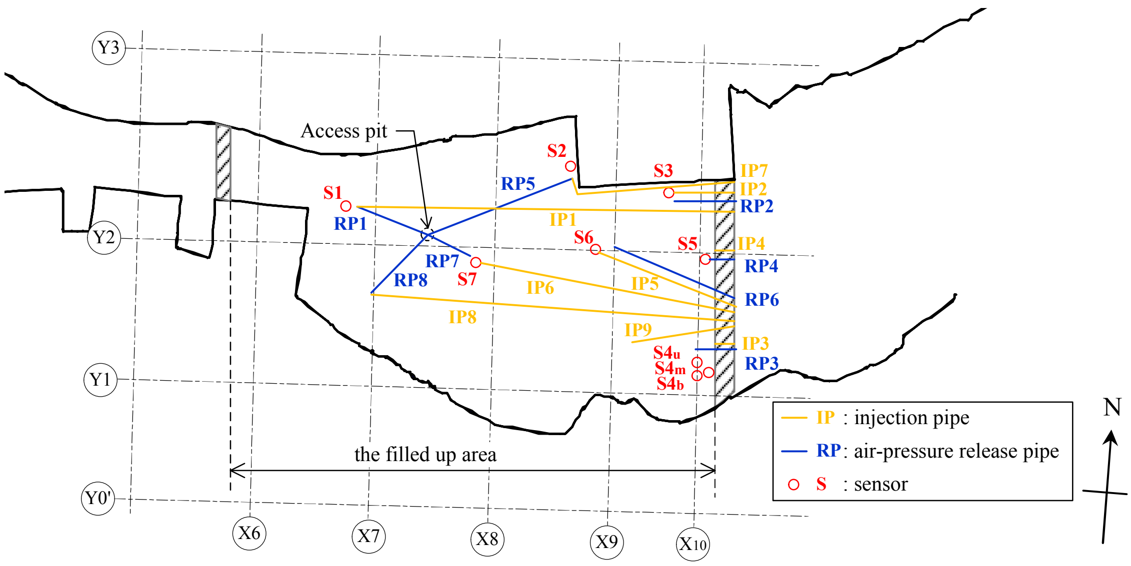


Figure 5. Locations of pipes to inject air-milk, air-pressure release pipes and contact sensors

(1) Pipes and contact sensors

(2) Mortar-bag bulkhead

Photo 4. Arrangement of pipes to inject air-milk, air-pressure release pipes and contact sensors

Table 4. Check items

	Timing	Check items
Filling condition	Before the work	1. Check if the selected material is suitable for filling the lava tube.
		2. Check if pipes are well arranged.
	In working	3. Check if the quality of air-milk is properly controlled.
		4. Check by sight through the existing access pit if the tube cavity is properly filled up.
		5. Check if the mortal touched contact sensors put on the crowns of the tube.
		6. Check if mortar starts spilling over through air-pressure release pipes.
Prevention of leak	Before the work	7. Check if the area enclosed with mortal bag bulkheads is completely sealed. The related check items include the followings :(a) Sealing gaps between steel-pipe piles and their side rocks, and (b) Sealing cracks of lava walls.
		8. Check if the floor of the lava tube was completely covered thin with air-milk for making the floor water-tight.
	In working	9. Check by sight if there is any sign of mortar leaks through the joints of bulkheads.
	Always	10. Check if there is any sign of water contamination in the nearby river(s).

3.5. Seismic Isolation Retrofit

Filling up the first lava tube was followed by the seismic isolation retrofit. Columns of the basement were cut at their top ends and 55 seismic isolators were placed just underneath the ground floor to seismically decouple the superstructure from its substructure. Simultaneously 5 oil dampers were installed on the same level of the basement to damp long-lasting oscillation of the superstructure. For the implementation of the seismic isolation system, the parking lot and the machineries in the basement had to be moved out to the other places. However, everything above the basement was kept as it was for continuing offering daily services to citizens. A temporary reinforcing work was done at the basement story in case of moderate earthquakes.

Figure 6. shows the locations of seismic isolators (40 natural rubber bearings of 650-1000 mm diameters and 15 high damping rubber bearings of 800-1000 mm diameters) and oil dampers (max. reduction capacity: 500-750kN). They were arranged for the optimum-balance.

Figure 7. shows the processes of the seismic isolation retrofitting. The retrofitting was done in the following steps:

1st step, pulling down walls and floors at basement

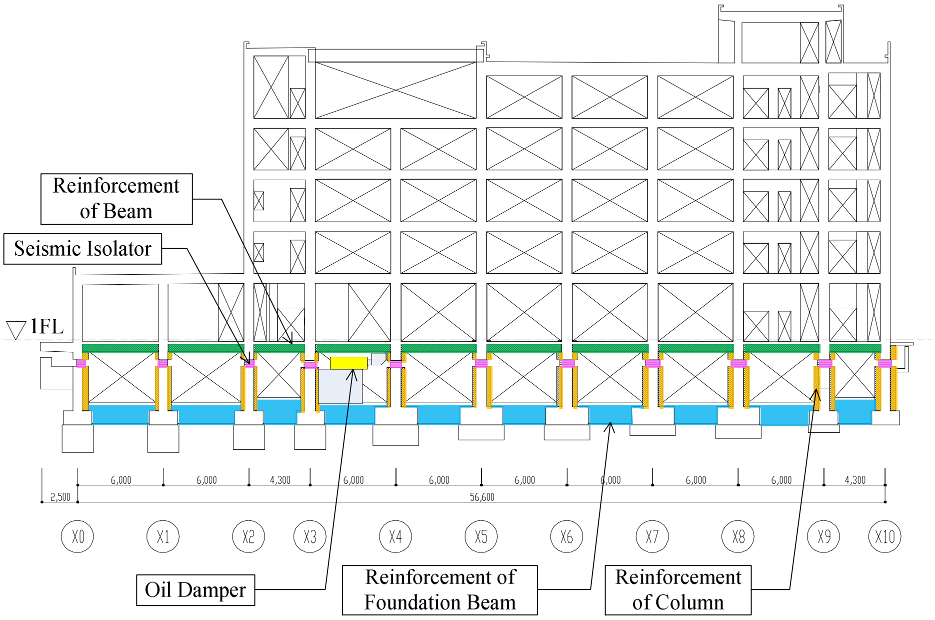
2nd step, both permanent and temporary reinforcements of existing beams and columns of the basement foundation and the ground floor

3rd step, giving temporary supports (shoring) to the superstructure by jacking it slightly up and cutting the columns of basement at their top ends

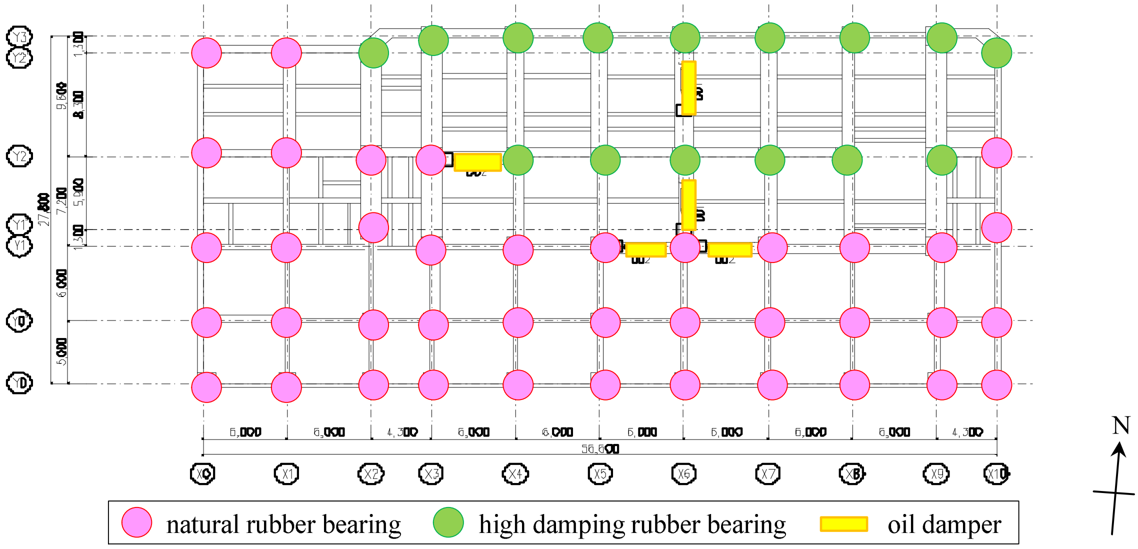
4th step, installation of seismic isolators

5th step, jacking down the superstructure on the installed isolators and removal of the temporary reinforcement

The seismic isolation retrofitting was completed about 18 months later.



(1) Section



(2) Basement plan

Figure 6. Locations of seismic isolators and oil dampers

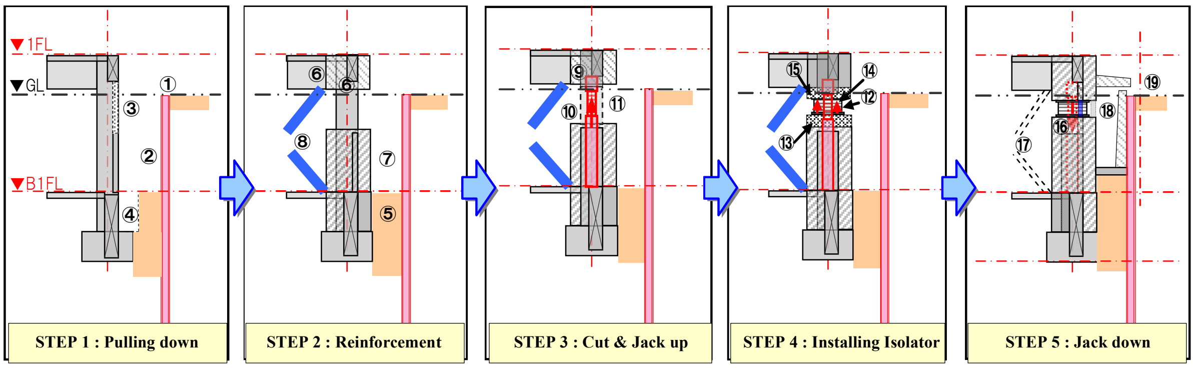
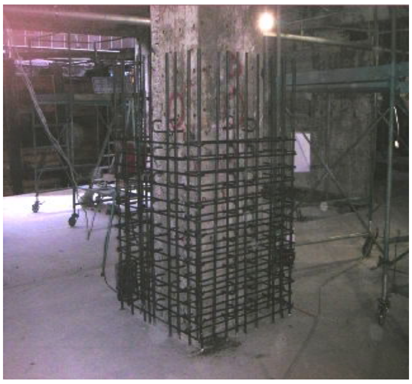


Figure 7. Steps of implementing seismic isolation system



(1) Foundation beam (2) Column

(3) Seismic isolator (4) Oil damper

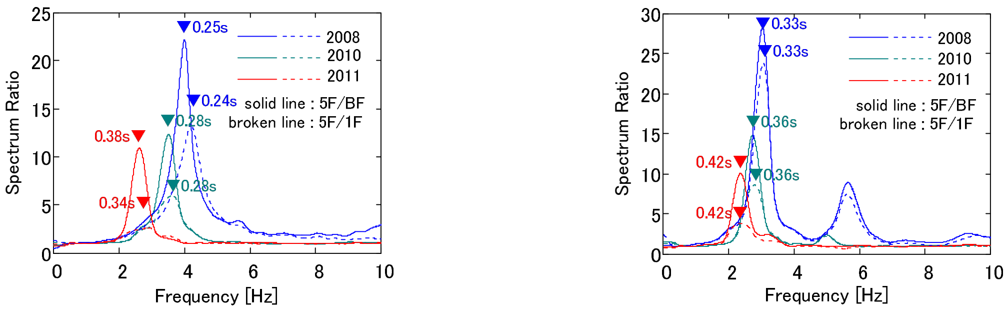
Photo 5. Photos of seismic isolation retrofitting works

4. MICRO-TREMOR OBSERVATION RESULTS

The micro-tremor observations were carried out to check out the change of ambient vibration of the entire building at three different times; before the retrofitting, after filling up the lava tube and after the retrofitting. Table 5. shows the dates of the observation. The change of the natural period of the building is shown in Figure 8. The period of the building became longer than the original one in 2008 after the removal of the walls in the basement in 2010. The period of the building got even longer by about 0.10-0.14s after installation of seismic isolators in 2011. The change of the period was surely due to the progress of the construction but it was not dramatic. Table 6. shows the change of the damping factors. The removal of the walls caused an approximately 1% reduction of the damping factor in north-south direction, and after installation of seismic isolators the damping factor slightly increased. In east-west direction, the damping factor hardly changed after the removal of the walls, and increased approximately 1.5% after installation of seismic isolators. Figure 9. shows yearly changes of the sway and rocking ratios. The ratios increased with the installation of seismic isolators.

Table 5. Dates of the observation

Date		Course of works			
		Filling up the lava tube	Walls in the basement	Reinforcement of beams and columns	Seismic isolators
The 1st	Sat. 8 Nov. 2008 (before retrofit)	Not finished	Existing	Not reinforced	Not installed
The 2nd	Sun. 19 Dec. 2010 (after filling up)	Finished	Removed	Reinforced partially	Not installed
The 3rd	Sun. 31 Jul. 2011 (after retrofit)	Finished	Renovated (installed seismic slit)	Reinforced	Installed

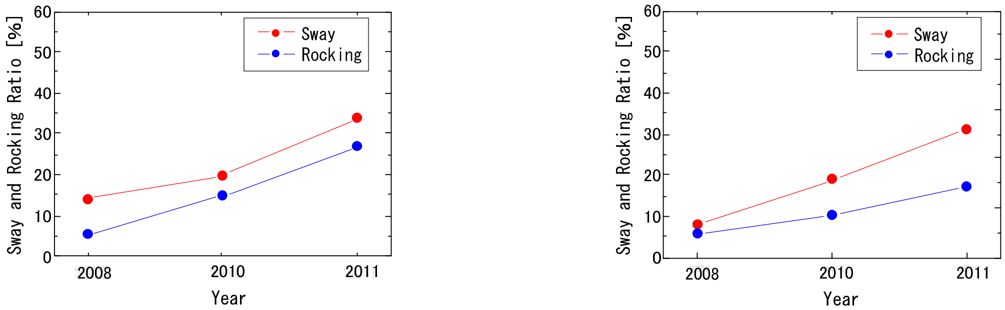


(1) NS direction (2) EW direction

Figure 8. Spectrum ratios (5F / BF, 5F / 1F)

Table 6. Damping factors

Year of observation	NS	EW
2008 (before retrofit)	3.5%	1.6%
2010 (after filling up the lava tube)	2.5%	1.5%
2011 (after retrofit)	3.0%	3.0%



(1) NS direction (2) EW direction

Figure 9. Sway and rocking ratios

5. CONCLUSION

It took about 7 years to complete the seismic isolation retrofit project of the Susono City Hall, and the city hall is now ready to function as a disaster management center in response to major scenario events such as the scenario Tokai Earthquake.
We sincerely hope that this project report provides a good precedent for municipalities under serious seismic threats.

ACKNOWLEDGEMENT

The micro-tremor observation and the spectrum analysis were conducted by members of Nakano laboratory, Institute of Industrial Science, the University of Tokyo. The detail design and the construction of this seismic retrofit were carried out by the Toda Corporation. The authors deeply appreciate their cooperation and supports.

REFERENCES

SAAF/Shizuoka Association of Architectural Firms. (2006 in Japanese). Manual for Seismic Evaluation and Seismic Retrofit of Existing Buildings in Shizuoka , SAAF

JBDPA/The Japan Building Disaster Prevention Association. (2001 in Japanese, 2005 in English). Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings, JBDPA

Asai T., Takahashi N., Choi H., Nakano Y. (2011). Vibrational Characteristics on a Five Stories Reinforced Concrete Building during the Seismic Retrofit. *Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan.* **B-2: Structures II**, 343-344.