DS '11 KOBE
International Symposium on
Disaster Simulation & Structural Safety in the Next Generation (DS'11)
September 17-18, 2011, JAPAN

# Seismic Response Analysis of Base-isolated Building Considering Collision with Retaining Wall

**Yoshinori KONNO,** *Graduate School of Architecture, Maebashi Institute of Technology*
*460-1, Kamisatori-machi, Maebashi-shi, Gunma 371-0816 JAPAN*
*Email: k-yoshinori_g@maebashi-it.ac.jp*
**Yoshikazu KANAI,** *Graduate School of Urban Environment and Information Sciences, Maebashi Institute of Technology*
*460-1, Kamisatori-machi, Maebashi-shi, Gunma 371-0816 JAPAN*
*Email: m0916501@ maebashi-it.ac.jp*
**Yoshio MANABE,** *Terrabyte Co, ltd*
*3-21-4, Yushima, Bunkyou-ku, Tokyo 113-0034 JAPAN*
*Fax: 03-5818-6889*
**Kazukuni NIWA,** *Terrabyte Co, ltd*
*3-21-4, Yushima, Bunkyou-ku, Tokyo 113-0034 JAPAN*
*Fax: 03-5818-6889*
**Haruji THUBOTA**, *Graduate School of Architecture, Maebashi Institute of Technology*
*460-1, Kamisatori-machi, Maebashi-shi, Gunma 371-0816 JAPAN*
*Email: tsubota-h@maebashi-it.ac.jp*
**Yoshiyuki KASAI**, *Graduate School of Urban Environment and Information Sciences, Maebashi Institute of Technology*
*460-1, Kamisatori-machi, Maebashi-shi, Gunma 371-0816 JAPAN*
*Email: kasai@maebashi-it.ac.jp*

***Keywords:*** Long-period pulse earthquake, Base-isolated building, Collision, Earth Simulator, Response analysis

## SUMMARY

A seismic base-isolation structure can reduce seismic force by increasing the natural period of the building. Kyoshin Network (K-net) has been observing long period earthquake waves called “Long period pulse earthquake”. There is a possibility of the base-isolated building to collide with retaining wall due to resonance between building natural period and long-period of the pulse earthquake. For the purpose of making clear the vibrational characteristics of base-isolated building considering collision with retaining wall, the three dimensional modeling and analysis of a building with isolators subjected to earthquake is expected. Therefore, two kinds of analytical model, single stick model and detailed FEM model are constructed and then the earthquake response of two kinds of model are computed using the Earth Simulator owned by JAMSTEC. According to analyses so far, collisions between the building and the retaining walls on both sides occur several times and therefore, evaluation of structural safety of the building and the retaining supporting structures due to each impact force becomes important.

## 1. Introduction

A seismic isolation structure can reduce seismic force by increasing the natural period of the building and has been used in many buildings since the 1995 Hanshin-Awaji earthquake. On the other hand, according to observation results of K-NET (Seismograph Network of NIED (National Research Institute for Earth Science and Disaster Prevention)), a seismic wave with a long period and large amplitude, which is called a long period pulse, is frequently observed even for strong local earthquakes. [1] Accordingly, there is the possibility of resonance phenomenon of a base-isolated building structure when the period of such a long period seismic wave matches the natural period of the building. In particular, large displacement may occur at the seismic isolation layer, and as a consequence, collision with the retaining wall is expected that may result in damage to the foundation or building structure.

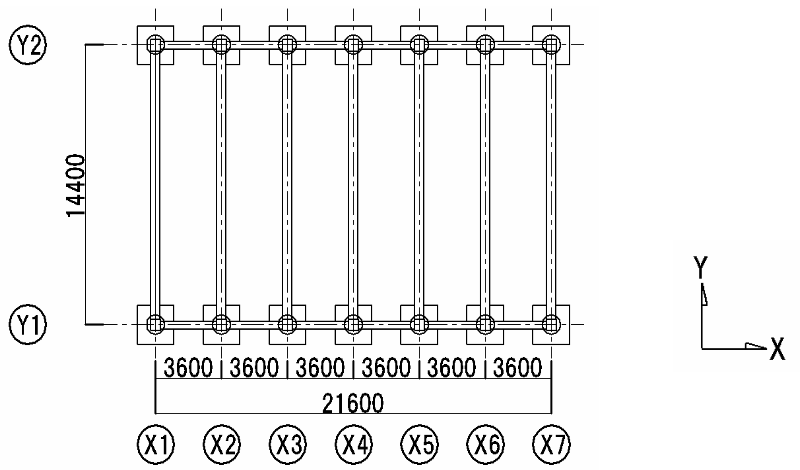
One of the authors[2], [3], [4] has been studying impact problems of structures due to earthquakes. One of their research studies is vibration behavior of collision with fuel graphite blocks of high temperature gas-cooled reactor (HTGR) core subjected to an earthquake. In this analysis, rigid block models based on the collision theory with the coefficient of restitution were used because of lack in computing power. However, advances in both computer performance and analysis program were remarkable and therefore, earthquake response analysis of a large analytical model of a base-isolated building in consideration of the collision with the retaining walls can be realized as shown in this paper.

On the other hand, one of the authors[5] proposed a simple response spectrum method based on identical impulses. In this study, when a single mass model with natural period T is subjected to time dependent impact load with duration time τ, impact response displacement can be easily evaluated in terms of impulses and τ/T.

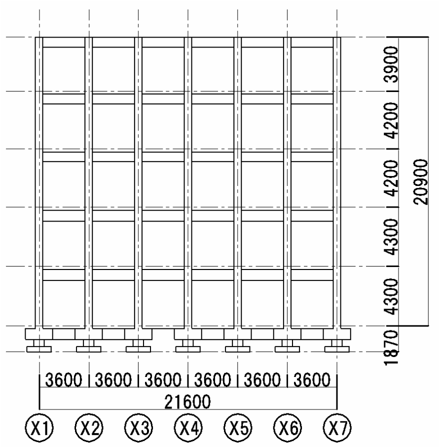
The research team of the authors is presently permitted to use the Earth Simulator owned by JAMSTEC (large scale parallel vector super-computer), which can process an enormous volume of data. Using this supercomputer, Takeda et al. [6], [7] conducted a sophisticated simulation analysis of a full-scale RC building on a shaking table to reproduce the results of the shaking table experiment. The result of the analysis indicated the feasibility of reproducing an actual scale test by the supercomputer using the explicit finite element impact analysis code LS-DYNA.[8]

To investigate the impact vibration response of a base-isolated building, three dimensional input of seismic motion and a detailed FEM model are desirable. Such an analysis requires the use of a supercomputer that can process enormous volumes of data.

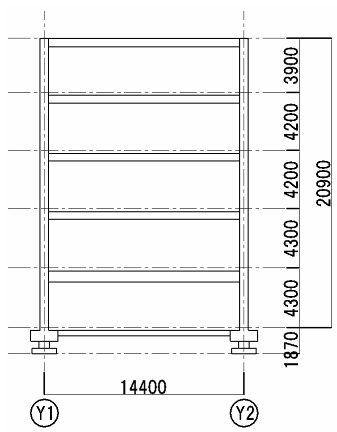
In this paper, for the first step, the dynamic response analysis with a simplified single stick model of an existing base-isolated building is performed to investigate the impact response of the seismic isolated building subjected to a long period pulse seismic wave. As the second step, the response is analyzed using a three dimensional detailed FEM model representing the building to investigate impact force to the structural elements.




**(a) Plan**




**(b) Section (X Direction)**




**(c) Section (Y Direction)**

**Figure 1 Framing Plan and Section of the Base-Isolated Building** [9], [10]

**Table 1 Summary of Isolator**[9], [12]

| Seismic Isolator | Laminated rubber by natural rubber system | Diameter of Laminated Rubber | 740mm |
|---|---|---|---|
| Horizontal Stiffness | 0.89kN/mm | Thickness of Rubber and Number of Layer | 4.4mm 61 layers |
| Vertical Stiffness | 1440kN/mm | Thickness of Steel Plate and Number of Layer | 2.3mm 60 layers |
| Allowable Horizontal Deformation | 375mm | Static Elastic Shear Modulus of Rubber | 0.549N/mm$^2$ |

## 2. Outline of Building Analyzed

The framing plan and framing section of the building are shown in Figure 1. The building is a five-story RC building with a frame structure consisting of six spans of 3.6m in the X direction and with shear walls of one span of 14.4m in the Y direction. Because no detailed structural data for the building structure (bar arrangement, openings in walls and floors, etc.) were available in constructing the analytical model, a trial design is performed based on the data that are available. The final designed model satisfies the allowable stress condition. The data of the seismic isolation layer are shown in Table 1. Although steel bar dampers are used in the actual building as the damper mechanism, they are neglected in the analysis.

## 3. Analysis Using Single Stick Model

### 3.1 Analytical Model

A simplified single stick model with six-concentrated masses and shear springs as shown in Figure 2 is employed for the first step analysis. The mass and spring stiffness of each story are shown in Table 2. The total mass of the building, including the seismic isolation layer, is 2,576t (weight 25.24 MN), and the natural period of the building is 2.79s. The material of the retaining wall is assumed to be an elastic material. The mass of the retaining wall on one side is 11.8t (weight: 0.12MN), and the natural period is 0.017s. The clearance between the seismic isolation layer and the retaining wall is 375 mm.

**Table2 Mass and Spring Stiffness Each Story** [10], [11]

| Story | Mass (t) | | Spring Stiffness (kN/mm) | |
|---|---|---|---|---|
| 5 | $m_5$ | 576 | $k_5$ | 2331 |
| 4 | $m_4$ | 347 | $k_4$ | 2957 |
| 3 | $m_3$ | 350 | $k_3$ | 3758 |
| 2 | $m_2$ | 363 | $k_2$ | 4524 |
| 1 | $m_1$ | 430 | $k_1$ | 6492 |
| Isolator | $m_{iso}$ | 582 | $k_{iso}$ | 13.1 |

### 3.2 Input Seismic Wave

The seismic motion observed during the Niigataken Chuetsu-oki Earthquake in 2007 at K-NET Kashiwazaki observation point (NIG018) in the NS direction is used as the input for the long period pulse seismic motion for the analysis. [1] In the seismic motion observed for duration of 294s, a portion of 30s that includes maximum acceleration is shown in Figure 3. A pulse wave with long period appears after 5s. Maximum acceleration is as large as 667gals, which is typical of long period pulse wave.

The results of the response spectrum analysis for the input seismic wave are shown in Figure 4. The maximum displacement response is 1,823mm at 2.55s, which is close to the natural period 2.79s of the building. Accordingly, resonance of the building is very likely to occur when this input seismic wave is applied to the building model.

### 3.3 Analytical Conditions

The analysis is conducted using time history response evaluation with the explicit finite element method. Furthermore, the response is analyzed considering the collision with the retaining wall by defining contact between the mass of the seismic isolation layer and the retaining wall. Seismic motion is applied to the ground for 30s. The time interval used is 44.6μs ($4.46 \times 10^{-5}$ s) and the output interval is 0.01s.

### 3.4 Analytical Results

The analytical results of the impact response analysis for displacement, velocity, and impact force of isolation layer are shown in Figures 5. From displacement time history, the building oscillates with a predominant period of 2.79s, which is very close to the natural period of the building. Regarding velocity time history, an oscillation accompanied by a high frequency oscillation is observed after the seismic isolation layer hit the retaining wall. This phenomenon seems to occur due to the overlap of the natural period of 2.79s of the building with the natural period of 0.017s of the retaining wall.

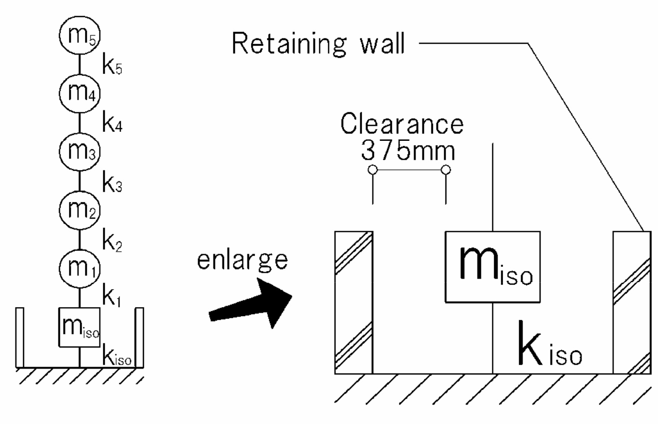



**Figure 2　Single Stick Model**

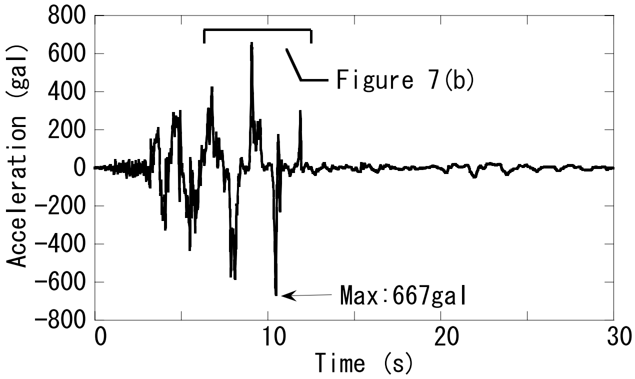
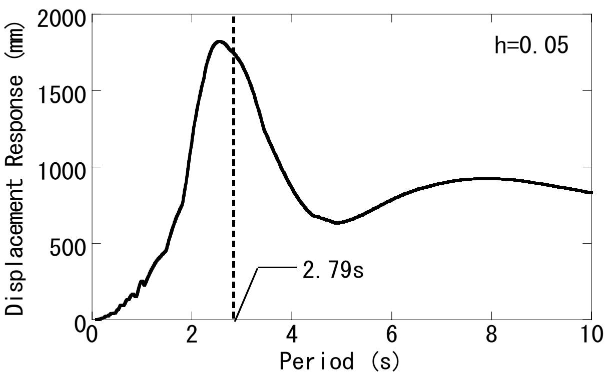
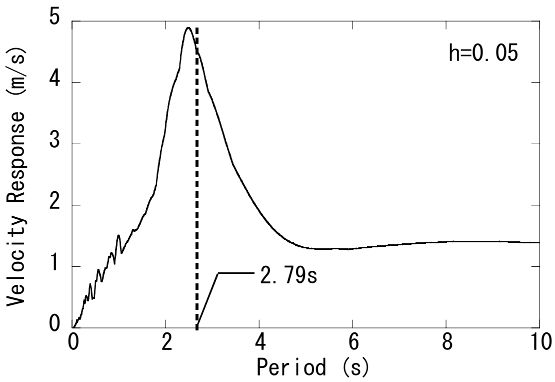


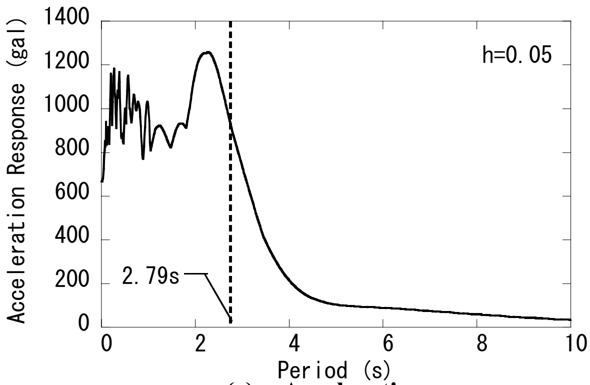

**Figure 3　Seismic Wave of NIG018･NS** [1]




**(a)　Displacement**

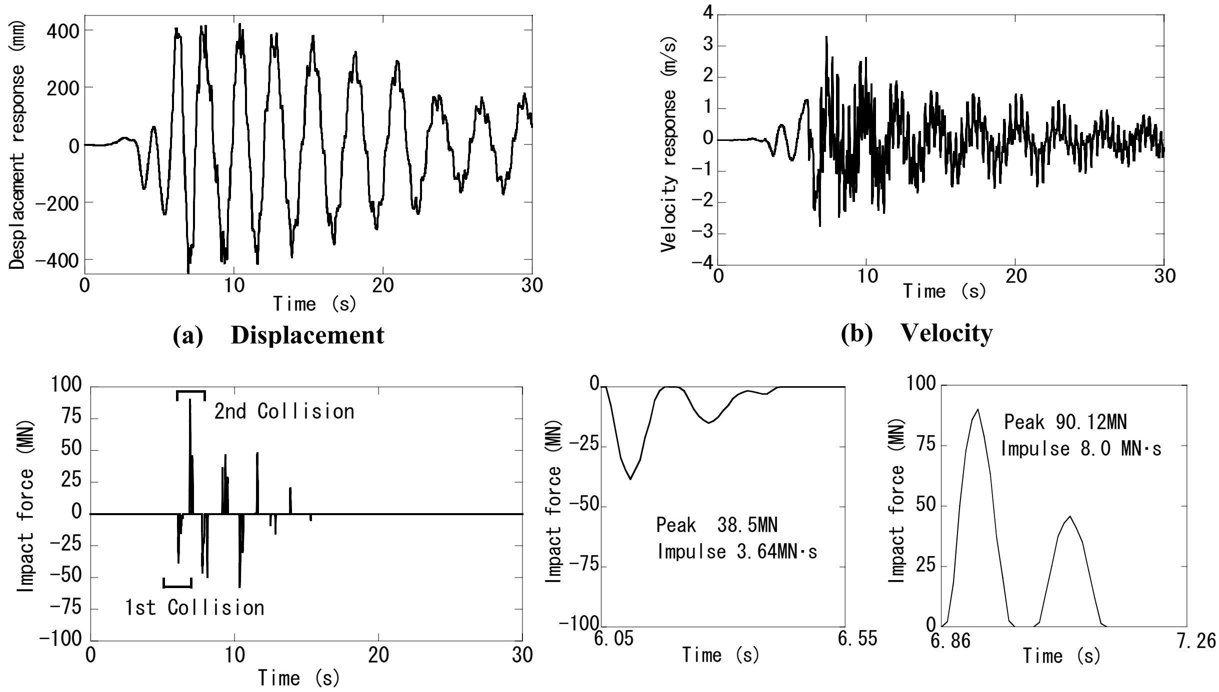



**(b)　Velocity**




**(c)　Acceleration**

**Figure 4　Response Spectrum of NIG018･NS**




**(a) Displacement** **(b) Velocity**

**(c) Overall of Impact Force** **(d) 1st Collision** **(e) 2nd Collision**

**Figure 5 Time History of Isolation Layer Response**

In Figure 5 (c), the positive value of the impact force indicates that the seismic isolation layer hit the retaining wall to the right (Figure 2) and the negative value indicates that it hit the retaining wall to the left (Figure 2). In this analysis, the collision of the seismic isolation layer with the retaining wall occurs nine times in 30s. The maximum impact force is 90.1MN at 2nd collision. As shown in Figure 5 (d) and (e), one collision seems to of two to three contacts.

The duration time of impact force due to collision is about 0.20s ~ 0.30s. The predominant period of the retaining wall becomes larger compared to the natural period 0.017s of the retaining wall itself because of increase in mass due to clinging of the building mass. The duration time τ and natural period T of the building are 0.20s~0.30s and 2.79s respectively and therefore, $\tau/T \fallingdotseq 1/10 \sim 1/14$ which is smaller than the border value 1/10 for "fracture due to impulse".[4] The response of the building due to collision tends to be decided by not the peak value of the impulsive force but the impulse in this region of $\tau/T<1/10$.

## 4. Analysis Using Detailed FEM Model

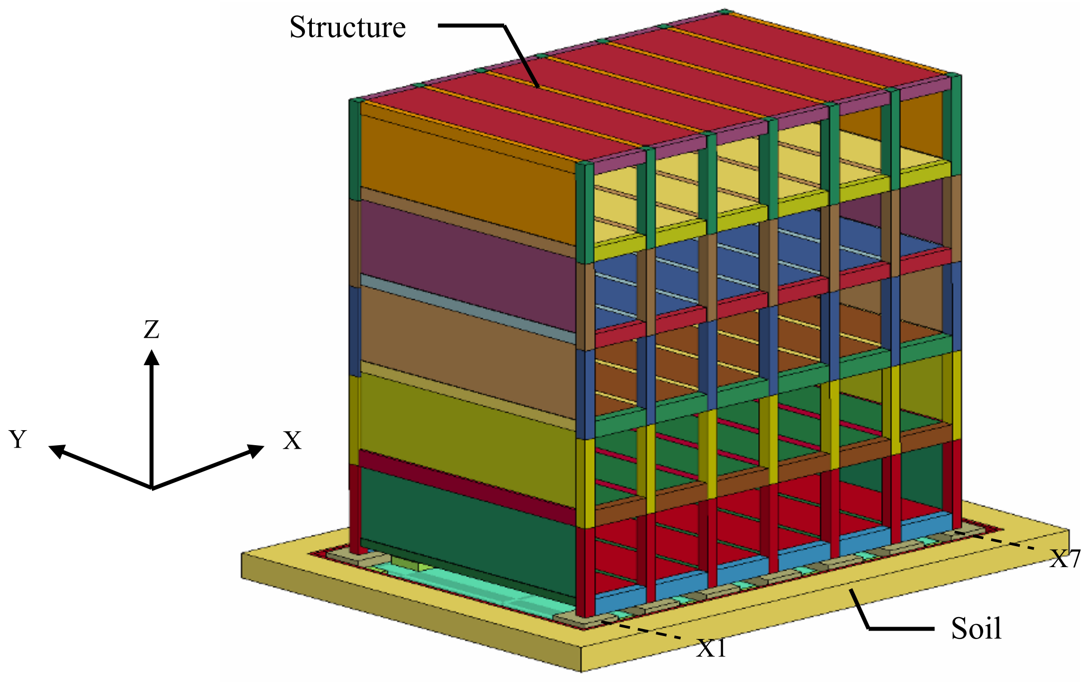
### 4. 1 Analytical Model

The model used in the second step analysis is shown in Figure 6. Concrete is represented by solid elements and the reinforcing bars are represented by beam elements as the actual arrangement in this model. Concrete and reinforcing bars are assumed to be fully bonded and have common nodes.

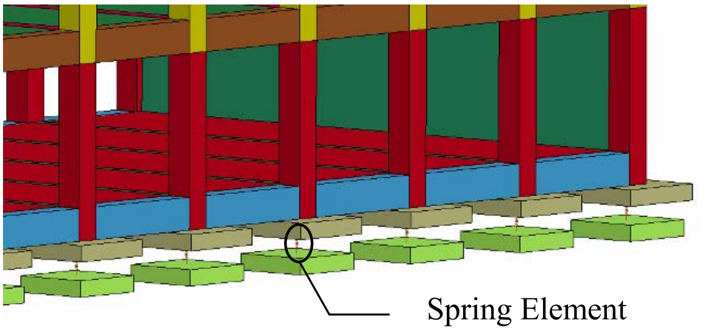
When the laminated rubbers are modeled as the actual arrangement, small elements should be formed in consideration of the other portions. In the explicit analysis, the time increment used in the analysis is determined by such small element according to the Courant condition.[13] Even when the Earth Simulator is used, this analysis requires a considerable amount of time. Accordingly, the model of isolation rubber is represented as spring element. Horizontal stiffness of the isolation rubber used was obtained from the experiment with the actual building. [12]

The shell elements are used as the ground for the model and acceleration due to the seismic wave is applied to this section. The reinforcing bars used in the model are assumed as isotropic elastoplastic material that take kinetic hardening into account. The reinforcing bars are assumed as SD295, which have yield strength of 295 $N/mm^2$, and a plastic hardening stiffness after the yield is assumed as 1/100 of the elastic stiffness.

For the concrete used in the model, material characteristics like strain rate effect, Ottosen's failure criterion, smeared crack, etc. are assumed. [6] [13] The design strength of Fc30 is used, and the tensile strength is assumed as 1/10 of the compressive strength. The number of elements of the used in the analysis is 3.92 million in total. The mass of the building is distributed among the nodes of the floor at each level to reflect the natural period of the single stick model.

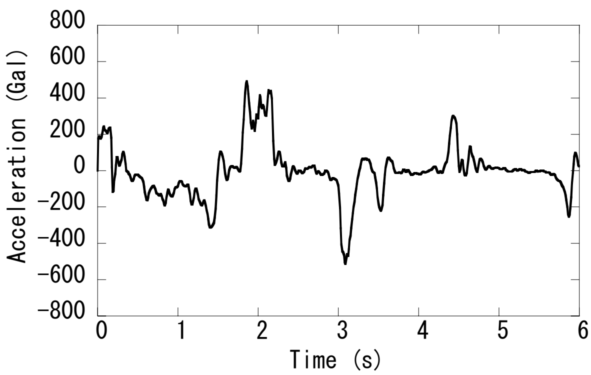



(a) Overall Building

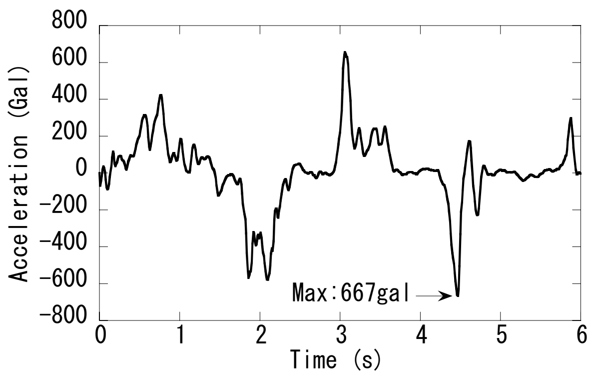



(b) Part of Enlarged Isolation Layer

**Figure 6 Perspective View of Detailed FEM Model**




(a) X Direction
(Original EW direction)




(b) Y Direction
(Original NS Direction)

**Figure 7 Input Seismic Wave [1]**

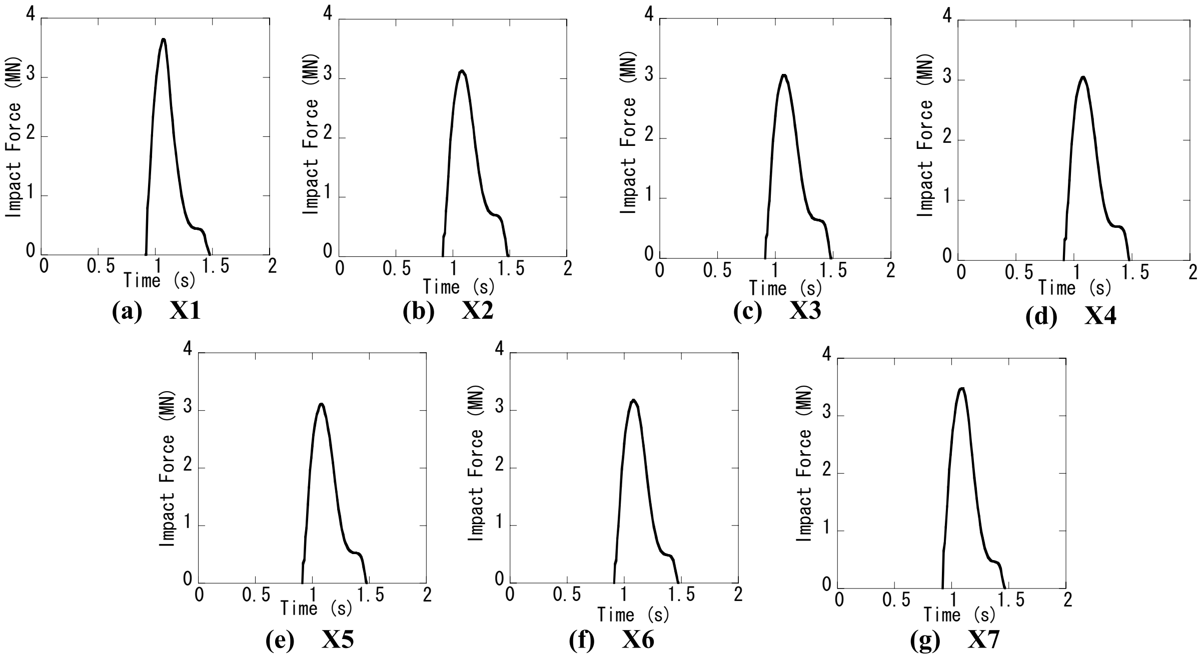



**Figure 8 Time History of Impact Force**

The total mass of the building is 2,576t (weight 25.24 MN) and natural period is 2.79s as same as the single stick model. The soil at the back of the retaining wall is also considered in the model. The material characteristics of the soil are established based on the past simulation analysis.[10],[11] Non-reflecting boundary condition for shear wave is assumed at the boundary of the model.

### 4. 2 Outline of Input Seismic Wave

In addition to the seismic motion in the NS direction used for the single stick model, the input of seismic motion in the EW direction is applied simultaneously[1]. The seismic waves used in the analysis are shown in Figure 7. Input of the seismic motion lasted 6.0s which included maximum acceleration, and seismic motion in original EW direction is applied in the X direction of the model and the seismic motion in the original NS direction is applied in the Y direction.

### 4. 3 Analytical Method

The explicit analysis code LS-DYNA[8] is used in the analysis. LS-DYNA is a program that incorporates an explicit solver and is suitable for analysis of the phenomenon that occurs in a very short time like an impact of the object. In the explicit analysis, it is not required to solve large inverse matrix; accordingly, it is more powerful than implicit analysis in the case of a large scale analysis. Computing performance depends on the program used, vector ratio, parallel ratio, and other factors, and the vector ratio of LS-DYNA exceeds 97%; thus, the compatibility of LS-DYNA with the Earth Simulator is very good. This combination has a record used in the FEM analysis of the building for seismic response as explained earlier.

### 4. 4 Outline of the Earth Simulator

There are limitations in using the Earth Simulator and 16 nodes (16 nodes × 8 CPUs = 128 CPUs), and the maximum consecutive time of 12 hours for the analysis are allowed.

Using this model, about 1.5s could be analyzed even when 16 nodes were used for 12 hours. Therefore, calculation of each 1.5s is successively executed using the restarting function of the analysis program.

### 4.5 Analytical Results

The analyses up to 1.5s are finished until now and therefore the results so far are shown as below.

Time histories of the impact forces due to the first collision are shown in Figure 8. Each time history of impact force has the same simple triangular shape and it means that the building collides perpendicularly with the retaining wall.

Sum of the peak values and impulses of the impact forces reach 26.7MN and 6.0MN・s respectively. The velocity of the building for colliding and moving away is 1.27m/s and 0.88m/s respectively and therefore change in momentum using the total mass of 2,576t is 5.5MN・s which is roughly the same as the above impulse value of 6.0MN・s.

Though further comparative study will be made between the detailed FEM and single stick model, the impact force[14] due to the earthquake response with collision is related to the modeling of the retaining wall and the neighboring soil, which is very important for the assessment of structural safety of a base isolated building.

## 5. Conclusion

Response analyses of the single stick model and the detailed FEM model were conducted, and vibrational characteristics due to the earthquake response with collision can be obtained. In the analysis, seismic wave input in two directions was applied for the detailed FEM model and the authors are planning an advanced analysis with seismic wave input in three directions taking vertical seismic motion into consideration as the next analytical stage.


## ACKNOWLEDGMENTS

In conducting this research, the authors would like to express their gratitude to use the Earth Simulator, which was permitted for the FY 2010 and 2011 Earth Simulator Collaboration Project of the Japan Agency for Marine-Earth Science and Technology.


## REFERENCE


[1] National Research Institute for Earth Science and Disaster Prevention, “Kyoshin - network”.

[2] Muto, K., Kasai, Y. et al. (1975) One-dimensional Vibration Test and Simulation Analysis for HTGR Core, Transactions of 3rd International Conference on Structural Mechanics in Reactor Technology, K8/8, pp.1- 10

[3] Muto, K., Kasai, Y. et al. (1977) Two-dimensional Vibration Test and its Simulation Analysis for a Vertical Slice Model of HTGR Core”, The Japan-U.S. Seminar on HTGR Safety Technology, Brookhaven National Laboratory, pp.1- 13

[4] Muto, K., Kasai, Y. et al. (1977) Two-dimensional Vibration Test and its Simulation Analysis for a Horizontal Slice Model of HTGR Core, The Japan-U.S. Seminar on HTGR Safety Technology, Brookhaven National Laboratory, pp.15 - 27

[5] Takeda, S., Kasai, Y. et al. (2011) Proposal for Impact Response Calculation Method using Response Spectrum based on Identical Impulses, Journal of Structural Engineering, Vol.57A, the Japan Society of Civil Engineers, pp.1225-1238 (in Japanese)

[6] Takeda, S., Kasai, Y. et al. (2010) Application of Impact Analysis Code based on the Explicit Time Integration to the Shaking Table Test for Three Story RC Frame, Japan Society of Civil Engineers, The 10th Symposium about Impact Problem on Structures, pp.301-306 (in Japanese)

[7] Takeda, S., Kasai, Y. et al. (2010) Application of Impact Analysis Code based on the Explicit Time Integration to the Shaking Table Tests of Full-scale Six Story RC Building, Part2, Bulletin of the Maebashi Institute of Technology No.14, pp.17-24 (in Japanese)

[8] LS-DYNA (general purpose transient dynamic finite element program), Livermore Software Technology Corporation (LSTC)

[9] Katsumata, H. et al. (2010), Experiments of Collision to Retaining Wall with Actual Base-Isolated Building、Symposium, To Think Building Response Characteristics against Pulse-Like Ground Motions, pp.9-18 (in Japanese)

[10] Takiyama, N. et al. (2010), Evaluation of Collision to Retaining Wall with Base-Isolated Building, Symposium, To Think Building Response Characteristics against Pulse-Like Ground Motions, pp.27-36 (in Japanese)

[11] Sato, K. et al. (2010) Evaluation and Influence on Response of Base-isolated Buildings in Collision to Retaining wall of resistance characteristics of Retaining Wall Including the Soil Behind, The 13th Japan Earthquake Engineering Symposium, pp.510-517 (in Japanese)

[12] Seki, S., Takeda T. (1987), Base-Isolated Building “High-tech R&D Center”, Building Disaster Prevention, August, pp.2-11 (in Japanese)

[13] Livermore Software Technology Corporation (LSTC), LS-DYNA KEYWORD USER’S MANUAL VOLUME Ⅰ, Ⅱ

[14] Muto, K., Kasai, Y. et al. (1978) Assessment of Dynamic Characteristics of Actual HTGR Core by Computer Code COLLAN (Part1) Fundamental Dynamic Characteristics by COLLAN 1, Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, Structural Division, Presentation No. 2185, pp.879 - 880 (in Japanese)