# Semi-Active Control Design for Base Isolated Structure Using Variable Damping Device Considered with Characteristic of Earthquake Motion and Sensor Placement

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#### SUMMARY:

This paper presents the method of semi-active control design considered with characteristic of earthquake motion and sensors placement for 4-story base isolated structure with 4 oil dampers whose damping coefficient can be changed at two steps. This method uses information of both sensor placement and structural response in the control design at the same time. We proposed the optimal sensor placement using fewer sensors compared with conventional control design method. The forgetting genetic algorithm is applied to multi-layered neural network and this algorithm is used not only to adjust the neural network parameters but also to forget the weak neural network in learning. This proposed method is effective to simplify the neural network, and as the results of simulation, the input information is made a choice. We can realize reduction of the structural response to use fewer sensors and decide the sensor placement under four different earthquake motions by the proposed control design method.

Keywords: Semi-Active Control, Base Isolation, Neural Network, Genetic Algorithm

## **1. INTRODUCTION**

Base isolated structures are referred to buildings with base isolators comprised of laminated rubber pads and damping devices. The base isolator may reduce seismic responses to the structure and control seismic vibrations from earthquakes. It contributes not only to secure the safety of the structural framework such as its columns and beams but also to prevent potential risks such as ceiling falling off, furniture and fixture tumbling or displacement and damages to the facilities. The effects of base isolated structures were also proven in the case of the 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011(Shimizu Corporation)(Saruta, 2011). Most of base isolators are currently of passive type with constant damping performances. Although there are semi-active type of base isolators have been developed to maximize the seismic capabilities against various characteristic of period and amplitude of earthquake motions, only few have applied to actual structures (Yoshida, 2001)(Shinozaki, 2005). In terms of risks of performance degradation of the damping devices due to its unwanted heating against long period or duration seismic motions, its control designs have been currently under study (Fukukita, 2011).

Under the circumstances, control designs were not considered for structures including sensor locations. Sensors are often placed at the top and bottom of a base isolated layer and the top of the building. This paper proposes the optimum sensor locations with fewer units with a rational control design considering effective layouts and response reductions, which shows a feasibility to achieve the target response reduction under the condition. This paper is considered to be a basic study to maintain and improve capabilities of seismic control even though a sensor is failed (improvement of tolerance to failure) as well as to seek a highly redundant layout of sensors to maintain and improve its control capabilities (higher redundancy), so that a control system is designed and reviewed for various seismic motions.

In this study, a 4-story base isolated structure model is used to study an optimum sensor layout with new concepts of control design to reduce responses. The seismic layer have an oil damper available to set damping coefficients in two levels, which is to apply two different damping coefficients based on the proposed control design. All the dampers shall be designed to have the same settings. The target control design is specified to have an intermediate value in a range between 'Hard' and 'Soft' levels for the displacement of isolation layer and building acceleration, which is differed from the case of a same damping coefficient setting for the maximum (Hard) and minimum (Soft) level. A neural network using Genetic Algorithm (GA) is applied to the control design. In particular, a network structure is simplified as forgetting is induced for connection weights with less bonding strength by applying Forgetting Genetic Algorithm (Shimura, 2001)(Fukumi, 1997)(Fukumi, 2001) to select the input data accordingly. Thus, the sensor layout can be determined at a stage of structure learning. As a result, the proposed control design shows the feasibility to reduce structural responses with fewer sensors, than that of conventional systems, which are placed in locations predetermined.

### 2. SEICMIC MOTION AND BASE ISOLATED STRUCTURES

#### 2.1. Seismic Motion

Seismic motions shown in this paper include: the waveform record of Kobe Marine Observatory (JMA Kobe) for the Southern Hyōgo prefecture earthquake in 1995 a near-field earthquake, the Kanto earthquake (Sato Wave) (Sato, 2001) a trench type large-scale earthquake, and Tokai-Tonankai Earthquake (Chubu Wave) (The Ministry of Land, 2004), and seismic motions calculated at Osaka Konohana Ward Office at the Tonankai Earthquake among the design values of long-period seismic motions studied in the public comments by the Ministry of Land, Transport and Infrastructure (The Ministry of Land). Figures 2.1 and 2.2 show the time history waveform of acceleration and the velocity response spectrum respectively.





Figure 2.1. Mathematical models for non-linear response history analysis

Figure 2.2. Velocity response spectrum (h=5%)



Figure 2.3. Structure model

Figure 2.4. Characteristics of variable oil damper

 Table 2.1. Specification of 4-degree-of-freedom structural model

Layer	Mass ( $\times 10^3$ kg)	Spring constant( $\times 10^8$ N/m)	Coefficient of viscous damping( $\times 10^6$ Ns/m)
4	1000	1.2317	0.7841
3	1000	1.8475	1.1764
2	1000	2.4633	1.5681
1	1000	0.1755	0.3351
Oil damper	-	0.2940	14.7 (max)
			0.8 (min)

### 2.2. Base Isolated Structure Models

A 4-story base isolated structure went through an analysis in this study, as shown in Fig. 2.3, which has natural rubber isolators and an oil damper with two levels of settings for damping coefficient at the bottom. The seismic layer is designed to be linear, with a natural period of 3.9 seconds and 2% of damping constant at a state without an oil damper as the superstructure is considered to be a one mass system. The superstructure is a linear type of equivalent shear model, and the damping constant is designed to be 2 % as an internal viscous damping of the structure against the primary natural period only for the superstructure. Table 2.1 shows various constants of the base isolated structures.

Oil dampers used in this study have a setting to change the levels of damping coefficient as the maximum and minimum values (Hard and Soft) by adjusting the degree of opening of the valve as shown in Fig. 2.4. The system is designed to relieve damping forces at about 640 kN. It is a Maxwell model connecting springs and dashpots in series. The specifications of the oil damper are as shown in Table 2.1. Time lag models are developed with the primary delay factor when changing the damping coefficient levels as shown in the following equation, as a response of an effective value to a command value.

$$G_d(s) = \frac{1}{Ts+1} \tag{2.1}$$

Note that the time constant is specified as T = 30 msec (Yoshida, 2001). The structure has four oil dampers with the characteristics as above.

#### **2.3. Equation of Motion and Equation of State**

The following show the equations of motion of the base isolated structures as shown in Fig. 2.3.

$$c_{s}(t)\dot{x}_{0}(t) - k_{s}(x_{1}(t) - x_{0}(t)) = 0$$
(2.2)

$$m_{1}\left(\ddot{x}_{1}(t)+\ddot{x}_{g}(t)\right)+\left(c_{1}+c_{2}\right)\dot{x}_{1}(t)+\left(k_{s}+k_{1}+k_{2}\right)x_{1}(t)-c_{2}\dot{x}_{2}(t)-k_{s}x_{0}(t)-k_{2}x_{2}(t)=0$$
(2.3)

$$m_{i}\left(\ddot{x}_{i}\left(t\right)+\ddot{x}_{g}\left(t\right)\right)+\left(c_{i}+c_{i+1}\right)\dot{x}_{i}\left(t\right)+\left(k_{i}+k_{i+1}\right)x_{i}\left(t\right)-c_{i+1}\dot{x}_{i+1}\left(t\right)-k_{i}x_{i-1}\left(t\right)-k_{i+1}x_{i+1}\left(t\right)=0 \quad (i=2,3)$$
(2.4)

$$m_4(\ddot{x}_4(t) + \ddot{x}_g(t)) + c_4\dot{x}_4(t) + k_4x_4(t) - c_4\dot{x}_3(t) - k_4x_3(t) = 0$$
(2.5)

Here,  $m_i$ ,  $c_i$ ,  $k_i$  refer to mass, damping coefficient and spring constant of each layer of the building respectively.  $c_s(t)$ ,  $k_s$  are for damping coefficient and spring constant for the Maxwell model.  $\ddot{x}_g(t)$  refers to ground accelerations.

As the state of quantity, considering oil damper's axis displacement  $x_0(t)$  under the Maxwell model, relative displacement from the ground to each layer  $x_i(t)$ , and relative velocity  $\dot{x}_i(t)$ , the above equation of motion is described as equations of state below:

$$\dot{\boldsymbol{x}}_{s}(t) = \boldsymbol{A}_{s}\boldsymbol{x}_{s}(t) + \boldsymbol{B}_{s}\left\{\boldsymbol{x}_{1}(t) - \boldsymbol{x}_{0}(t)\right\}\boldsymbol{u}(t) + \boldsymbol{D}_{s}\ddot{\boldsymbol{x}}_{g}(t)$$
(2.6)

$$u(t) = \frac{1}{c_s(t)} \tag{2.7}$$

$$\boldsymbol{x}_{s}(t) = \begin{bmatrix} x_{0}(t) & x_{1}(t) & \cdots & x_{4}(t) & \dot{x}_{1}(t) & \cdots & \dot{x}_{4}(t) \end{bmatrix}^{T}$$
(2.8)

Accordingly, the structure model in this study is considered to be a bilinear system, as its unique feature is to have the term for a control input u(t) being one of the functions of the quantities of state.

### **3. CONTROL SYSTEM DESIGN**

#### 3.1. Multi-layered Neural Network

This paper proposes a new design method, incorporating an effective sensor layout to reduce responses into the control system design, which should also be effective to reduce an absolute acceleration of each layer of the structure and displacement of base isolated layers. The control system design employs the 3-layered neural network including input, intermediate and output layers, as shown in Fig. 3.1, to specify the damping coefficient  $c_s(t)$  of oil dampers of Eq. (2.7). The input layer has eight units including the absolute acceleration of each layer and relative displacement from the ground (the very bottom layer  $x_1(t)$  shows the base isolated layer displacement), eight units for the intermediate layer and one unit for the output layer. The four oil dampers are given with the same switching signals for its damping coefficient. The following are the calculation of each layer.

Input layer: 
$$O_{pi} = X_{pi}, i = 1, 2, \dots, n_i$$
 (3.1)

Intermediate layer: 
$$u_{pj} = \sum_{i=1}^{n_i} w_{ji} O_{pi} + \theta_j, \quad j = 1, 2, \dots, n_j$$
 (3.2)

$$O_{pj} = f_h \left( u_{pj} \right) \tag{3.3}$$



 $\emptyset$ : Linear neuron  $\emptyset$ : Sigmoid neuron  $\oint$ : Threshold neuron

Figure 3.1. Structure model

Output layer: 
$$u_{pk} = \sum_{j=1}^{n_j} w_{kj} O_{pj} + \theta_k, \quad k = 1, 2, \dots, n_k$$
 (3.4)

$$O_{pk} = f_o\left(u_{pk}\right) \tag{3.5}$$

Transfer function (input layer --> intermediate layer):  $f_h(x) = \frac{2}{1 + \exp(-2x)} - 1$  (3.6)

Transfer function (input layer --> intermediate layer): 
$$f_o(x) = \begin{cases} 1 & (x \ge 0) \\ 0 & (x < 0) \end{cases}$$
 (3.7)

Here, w and  $\theta$  are a connecting weight and threshold value respectively. The values for the input layer are normalized to use with a relative displacement of each layer for the case of Soft, and an absolute acceleration for Hard.

### **3.2. Learning Procedure**

In terms of seismic responses, which remain unknown to predict the scale of responses depending on the control design, it is difficult to apply some lessons learnt in adjusting parameters of connecting weight w and threshold  $\theta$  for a multi-layered neural network. Therefore, the Genetic Algorithm, one of the representative optimization methods, is used to apply such parameter adjustments to determine connecting weight w and threshold  $\theta$  in order to meet an evaluating function specified. A unique feature of this study is to add a forgetting process to eliminate a connecting weight with less bonding strength from a regular Genetic Algorithm at the learning process, aiming for reducing the target response with fewer number of dampers, as well as to add a term of the bonding strength of the entire connecting weights to the evaluating function.

There should be 20 chromosomes, as a code of connecting weight w and threshold  $\theta$  per chromosome for each layer. Then, fitness is calculated based on the evaluating function below for a chromosome.

$$f = p_a p_x \left( f_a + f_x + f_{nn} \right)$$

$$f_a = \exp\left(-\frac{a^{\max} - a_{\min}}{a_{\min}}\right), \quad f_x = \exp\left(-\frac{x^{\max} - x_{\min}}{x_{\min}}\right), \quad f_{nn} = \exp\left(-\frac{NN_w}{a_{nn}}\right)$$
(3.8)

Here,  $a^{\text{max}}$ ,  $x^{\text{max}}$  are the absolute acceleration of each layer and the maximum displacement from the ground respectively.  $NN_w$  is the total of the connecting weights  $w_{ij}$  and  $w_{jk}$  of the input and intermediate layers, and the intermediate and output layers, as shown below.

$$a^{\max} = \max\left(\max\left|\ddot{x}_{i}\left(t\right) + \ddot{x}_{g}\left(t\right)\right|\right), \quad i = 1 \sim 4$$
(3.9)

$$x^{\max} = \max\left(\max|x_i(t)|\right), \quad i = 1 \sim 4$$
 (3.10)

$$NN_{w} = \sum_{i=1}^{input\_num} \sum_{j=1}^{num} \left| w_{ij} \right| + \sum_{j=1}^{hidden\_num} \sum_{k=0}^{num} \left| w_{jk} \right|$$
(3.11)

Here,  $a_{\text{max}}$ ,  $a_{\text{min}}$ ,  $x_{\text{max}}$  and  $x_{\text{min}}$  are the maximum values ( $a_{\text{max}}$  for Hard, and  $a_{\text{min}}$  for Soft,) of the absolute acceleration if the damping coefficient remains unchanged at either state of Hard and Soft, and the maximum values of the relative displacement ( $x_{\text{min}}$  for Hard,  $x_{\text{max}}$  for Soft) respectively.  $a_{m}$  is the total number of chromosome ( $a_{m} = 20$ ).

 $f_a$  and  $f_x$  in Eq. (3.8) are the absolute acceleration and evaluating function. The higher relative displacement, the smaller  $f_a$ ,  $f_x$ .  $f_{nn}$  is a parameter to show a bonding strength, that the smaller this value, the less bonding strength.  $p_a$  and  $p_x$  are the absolute acceleration and penalty function concerning the relative displacement from the ground respectively. The absolute acceleration without control design (if a damping coefficient remains unchanged for either Soft or Hard) and the response value of relative displacement are calculated to make the evaluating value low as below.

Penalty function of an absolute acceleration

$$p_{a} = \begin{cases} 1.0 & \left(a^{\max} < a_{\min}\right) \\ 0.6 & \left(a^{\max} \le a_{\max} \text{ and } a^{\max} > a_{\min}\right) \\ 0.1 & \left(a^{\max} > a_{\max}\right) \end{cases}$$
(3.12)

Penalty function of a relative displacement

$$p_{x} = \begin{cases} 1.0 & (x^{\max} < x_{\min}) \\ 0.6 & (x^{\max} \le x_{\max} \text{ and } x^{\max} > x_{\min}) \\ 0.1 & (x^{\max} > x_{\max}) \end{cases}$$
(3.13)

Equations (3.12) and (3.13) show that a structural response value when the damping coefficient remains unchanged for Soft (minimum) and Hard (maximum) as a criteria of the penalty functions.

Given the equations above, a fitness calculation is conducted for 20 individuals, to select the next generation individuals as 2 from Elitist Preserve Strategy and 4 from Roulette Strategy. These parents are randomly selected to form a pair, in order to generate 4 individuals per each of random pairing for uniform crossover and mutation. Here, the two individuals given by Elitist Preserve Strategy are copied to make the connecting weight 0 if the connecting weight w is the threshold. This process is called "forgetting", and the method is referred to as Forgetting Genetic Algorithm. As repeating the calculation, 16 next generation individuals are generated, in addition to 4 to randomly be generated. This cycle of process for a generation has been repeated to seek an individual with higher fitness.

If an output from the multi-layered neural network is as p(t), 0 or 1 would be output from p(t). The damping coefficient  $c_s(t)$  is determined as the equations below.

$$c_{s}(t) = (1 - p(t))c_{s\max} + p(t)c_{s\min}$$
(3.14)

$$p(t) = 0 \text{ or } 1$$
 (3.15)

Here,  $c_{smax}$  and  $c_{smin}$  are the damping coefficients of Hard and Soft for oil dampers. Thus, Eqs. (3.14) and (3.15) are used for selecting either Hard or Soft as a damping coefficient depending on dampers.

The above learning processed was undergone for the waveforms from JMA Kobe as a near-field earthquake, Kanto earthquake (Sato Wave) (Sato, 2001) with long-period seismic motions, Tokai-Tonankai earthquake (Chubu waveform) (The Ministry of Land, 2004) and the waveform calculated at Osaka Konohana Ward Office in the case of Tonankai earthquake as a design long-period seismic motion as given by the Ministry of Land, Transport and Infrastructure.

## 4. SIMULATION

Firstly, a simulation is conducted using the control system designed as Chapter 3 for a 4-story model, shown in Fig. 2.3, with the JMA Kobe waveforms or a near-field earthquake, to input for a review of the result of control design. Figure 4.1 shows the way of bonding of a multi-layered network when the total of  $p_a + p_x$  is 1.2 for the penalty function showing a control capability. The thin and thick lines in the figure show the states of initial bonding for the network and the bonding of a network remained after forgetting respectively. Figure 4.2 shows the absolute acceleration of the top layer  $\ddot{x}_4(t) + \ddot{x}_e(t)$ ,

displacement of base isolated layer  $x_1(t)$ , damping coefficient  $c_s(t)$ , switching signal p(t), and a time history waveform for the acceleration of JMA Kobe waveform. Figure 4.3 shows the absolute accelerations of each layer, relative displacement from the ground and the maximum value distribution of deforming angle between layers. Figure 4.1 reveals that the initial value was for a neural network to connect all input layers including eight units of input layer, eight units of intermediate layer, and one unit of output layer, although it turned to be that of five units of input layer and one unit of intermediate layer, showing a significant reduction of bonding strength of the units. This refers to that a desired damping capability is obtained only with a small bonding status, as shown in Fig. 4.1, by placing the displacement sensors at the first, third and fourth layers and the acceleration sensors at the second and third layers. This means that the structure has a sufficient seismic control capability with a small number of sensors, and the sensor layout is also reasonable enough. It is then confirmed to be feasible by applying Forgetting Genetic Algorithm. Therefore, it proves that the fewer number of bonding would contribute to a significant reduction of calculation of the control system. Figures 4.2 and 4.3 also show that the absolute acceleration and displacement of base isolated layers are in the range of the intermediate value of Hard and Soft for the top layer, if the level of control is changed by the method proposed in this paper. Figure 4.4 shows the time history waveform of velocity of an oil damper and relationship of velocity and damping force of the oil damper. According to the figure, it reveals that the oil damper is activated as specified in Fig. 2.4 and its relief load is exceeded when selecting Hard as the setting.

Next, regarding the results of simulation when the Kanto earthquake (Sato Wave) (Sato, 2001), a long-period seismic motion, is used as input seismic waveform, Figs. 4.5, 4.6 and 4.7 show the state of a neural network connection, the time history waveform, and the maximum value distribution of the response respectively. In terms of the results of simulation with the Tokai-Tonankai earthquake (Chubu Wave) (The Ministry of Land, 2004), a long-period seismic motion with a significant seismic force in three seconds per cycle, as the input seismic waveform, Figs. 4.8, 4.9 and 4.10 show the state



**Figure 4.1.** Multi-layered neural network in case of  $p_a + p_x = 1.2$  (JMA Kobe)



**Figure 4.2.** Waveforms of structural response in case of  $p_a + p_x = 1.2$  (JMA Kobe)



**Figure 4.3.** Maximum disturbance of response in case of  $p_a + p_x = 1.2$  (JMA Kobe)



**Figure 4.4.** Isolation velocity and damping force in case of  $p_a + p_x = 1.2$  (JMA Kobe)







**Figure 4.6.** Waveforms of structural response in case of  $p_a + p_x = 1.2$  (Kanto)



**Figure 4.7.** Maximum disturbance of response in case of  $p_a + p_x = 1.2$  (Kanto)



**Figure 4.8.** Multi-layered neural network in case of  $p_a + p_x = 1.2$  (Tokai-Tonankai)











**Figure 4.11.** Multi-layered neural network in case of  $p_a + p_x = 1.2$  (Tonankai)



**Figure 4.12.** Waveforms of structural response in case of  $p_a + p_x = 1.2$  (Tonankai)



**Figure 4.13.** Maximum disturbance of response in case of  $p_a + p_x = 1.2$  (Tonankai)

of neural network connection, the time history waveform, and the maximum value distribution of the response respectively. Furthermore, regarding the results of simulation of Tonankai earthquake (Osaka Konohana) (The Ministry of Land), with the peak for a longer period than 3.9 seconds of the primary natural period of a base isolated structure model, Figs. 4.11, 4.12 and 4.13 show the state of neural network connection, the time history waveform, the maximum value response respectively. It shows a significant reduction of the number of units connected even for different seismic motions. It also shows the structure is effective to reduce seismic responses with fewer sensors, although the sensor layouts are depending on seismic waveforms. Figures 4.7, 4.10 and 4.13 show that both absolute acceleration and displacement of the base isolated layer of the top layer are in the intermediate range of Hard and Soft, which achieves the target control value. As a result, the three seismic waveforms are also confirmed to allow the oil dampers to activate as specified in Fig. 2.4, and the relief load is

exceeded when selecting Hard as the setting, in the same manner of the JMA Kobe waveform.

## **5. CONCLUSION**

This paper studies an optimum layout of sensors for a 4-story base isolated structure model, as applying the new control design concept using Forgetting Genetic Algorithm for switching rules of the oil dampers at the base isolated layer, which have two levels of setting for its damping coefficient to reduce seismic responses. As the target, a damping coefficient is designed to be in an intermediate range between Hard and Soft for displacement of the base isolated layer and the structural acceleration when changing the levels. This is a difference from the case when the value remains the same for both maximum (Hard) and minimum (Soft) settings. As a result of the simulation of control effects against the four different types of seismic waveforms including a near-field earthquake with a short cycle of frequencies, and other three kinds of long-period seismic motions with different characteristics, it is confirmed that the sensor layout can be determined at a learning stage. The response of the base isolated structure can also be reduced once the number of connection from the input to output layer is significantly reduced.

Accordingly, this paper explains that the proposed method is effective, which is to design a system to control seismic motions with prominent characteristics known in advance. Although seismic motion related data are limited to obtain before actual earthquakes, the concept of sensor layout stated in this method as a basic research is to propose a way to improve fault tolerances to maintain controls and prevent an extreme degradation of performance in the case of sensor failures, as well as to secure redundancies to maintain and improve the performances in controlling the system. Thus, the concept proposed in this study is effective to apply to actual systems once it is further advanced.

#### REFERENCES

- Shimizu Corporation website, The Great Tohoku Earthquake related technical report effects of base isolated structures. See also URL http://www.shimz.co.jp/theme/earthquake/effect.html.
- Saruta, M., Okada, K., Nakamura, Y., and Hasebe, M., (2011). The 2011 off the Pacific Coast of Tohoku Earthquake and Response of Base Isoalted Structures. *Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan*, B-2:Structures II, 629-630.
- Yoshida, K., and FUJIO, T., (2001). Bilinear Optimal Control Theory and its Application to Semi-Active Vibration Isolation Control. *Transactions of the Japan Society of Mechanical Engineers, Series C*, 67:656, 992-998.
- Shinozaki, Y., Toyama, J., Nagashima, I., Maseki, R., Kitagawa, Y. and Yoshida, K., (2005). Development and Application of Semi-active Base-Isolation System (Part 1) – (Part 6). Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, B-2:Structures II, 723-734.
- Fukukita, A., and Takahashi, M., (2011). Semi-Active Control for Base Isolated Structure Using Response Evaluator Subjected to Long-Period Earthquake Ground Motion. *Transactions of the Japan Society of Mechanical Engineers, Series C*, 77: 777, 1649-1660.
- Shimura, A., and Yoshida, K., (2001). Rule extraction with connection forgetting from neural network DYC controller. *Transactions of the Japan Society of Mechanical Engineers, Series C*, **67:661**, 2837-2842.
- Fukumi, M., and Akamatsu, N., (1997). A Genetic Algorithm with Deterministic Mutation Based on Neural Network Learning. *The Institute of Electronics, Information and Communication Engineers, D-II*, J80-D-II:10, 2800-2807.
- Fukumi, M., and Mitsukura, Y., (2001). Automatic Extraction of Tumors by Using Neural Computation. Society of Signal Processing Applications and Technology of Japan, **12**, 13-18.
- Sato, T., and Dan, K., (2001). Wide band strong motion prediction of areas around Tokyo by using the Kanto earthquake. Recommendation for the Design of Base Isolated Buildings, Architectural Institute of Japan, 263-274.
- The Ministry of Land, Transport and Infrastructure Organization Chart of Chubu Regional Development Bureau and Consortium, (2004). Basic Seismic Motion Data for Seismic Reinforcement of Buildings in Sannomaru, Nagoya City considering Regional Characteristics (Summary), 48.
- The Ministry of Land, Transport and Infrastructure website, The Request for Public Comments for Provisional Measures against Long Period Seismic Motion for Super High Rise Buildings. See also URL http://www.mlit.go.jp/report/press/house05\_hh\_000218.html.