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Sequential Parameter Optimization Method for Updating Nonlinear Seismic Response Analysis Model of Nuclear Power Plant

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ABSTRACT

In order to predict the response of buildings in nuclear power plant during an earthquake and evaluate their seismic performance, it is important to construct an analytical model that reflects actual conditions. When constructing an analytical model, it is necessary to set restoring force characteristics that are appropriate for reproducing the building's response during an earthquake. Against this background, we have proposed a sequential parameter optimization method that can estimate the restoring force characteristics of buildings. In this paper, in order to grasp the scope of application of the proposed method, we use the method to estimate the tangent stiffness, relative displacement, and restoring force characteristics of buildings with various restoring force characteristics and examine the estimation accuracy.

INTRODUCTION

When the buildings in nuclear power plant are subjected to repetitive external forces such as earthquakes, which can accumulate damage and degrade their seismic performance. Therefore, in order to predict the response of existing buildings during earthquakes that may occur in the future, it is important to update the analytical model constructed at the time of design to one that is appropriate for actual conditions. In addition, it is important to establish the restoring force characteristics that are adequate to reproduce the seismic behavior of the structure.

Previous studies have attempted to identify the vibration characteristics of buildings during earthquakes using system identification methods such as the ARX model (Loh, C.-H. and Lin, H.-M., 1996) and subspace methods (Yoshimoto, R., Mita, A., and Okada, K., 2004). However, these methods are based on the assumption of a linear system and are not suitable for system identification of buildings that exhibit strong nonlinearity.

In the previous studies, particle filters (Ishizaka, R. and Hida, T., 2022) and unscented Kalman filters (Meiliang, W. and Andrew, S., 2007) were used to estimate nonlinear restoring force characteristics. However, these methods identify parameters of the pre-defined restoring force characteristics, and thus require the setting of restoring force characteristics for each building, making them less versatile. The authors (Ihara, S. and Hida, T., 2023) applied an improved particle filter to strong-motion records to estimate the tangential stiffness of building restoring force characteristics as they change from moment to moment and the building response. However, the method could only be applied to cases in which the tangential stiffness at unloading was almost equal to the initial stiffness, making the method less versatile.

Based on the above background, we propose the sequential parameter optimization method for the purpose of estimating nonlinear restoring force characteristics of various buildings, in which parameters are optimized from time to time using strong motion records. To investigate the estimation accuracy, we perform numerical analyses using nonlinear seismic response analysis of a SDOF system. In this study, we use the bi-linear model, slip bi-linear model, and NCL model for the restoring force characteristics. Then, the tangential stiffness, relative displacement, and restoring force characteristics of the system with various initial natural period are estimated by using the sequential parameter optimization method.

OVERVIEW OF THE SEQUENTIAL PARAMETER OPTIMIZATION METHOD

A conceptual diagram of the proposed method is shown in Figure 1. The objective function $f_{\{k_{(t)}^n\}}$ is the square of the error between the observed increment of absolute acceleration $\Delta\ddot{x}_{\mathrm{obs}}$ and the calculated increment $\Delta\ddot{x}_{\mathrm{calc}}$ calculated by the equation of motion of the SDOF system, as shown in the following equation.

$$f_{\{k_{(t)}^n\}} = \left\{\Delta\ddot{x}_{\mathrm{obs}(t)} - \Delta\ddot{x}_{\mathrm{calc}(t)}^n\right\}^2 \tag{1}$$

where n is the number of iterations and $\Delta\ddot{x}_{\mathrm{obs}(t)}$ and $\Delta\ddot{x}_{\mathrm{calc}(t)}^n$ are expressed as

$$\Delta\ddot{x}_{\mathrm{obs}(t)} = \ddot{x}_{\mathrm{obs}(t)} - \ddot{x}_{\mathrm{obs}(t-1)} \tag{2}$$

$$\Delta\ddot{x}_{\mathrm{calc}(t)}^n = -\left\{k_{(t)}^n \Delta x_{(t)}^n + c_{(t)}^n \Delta\dot{x}_{(t)}^n\right\}/m \tag{3}$$

where t is the time step number, m is the building mass, k is the stiffness, c is the damping coefficient, $\Delta x_{(t)}^n$ and $\Delta\dot{x}_{(t)}^n$ are the relative displacement and relative velocity increments. the following equation is an update formula for the tangential stiffness k at the n-th update in the time step t.

$$k_{(t)}^n = k_{(t)}^{n-1} - \alpha\nabla f_{\{k_{(t)}^{n-1}\}} \tag{4}$$

where α is a parameter that determines the update width. The slope $\nabla f_{\{k_{(t)}^n\}}$ of the objective function at stiffness $k_{(t)}^n$ at the n-th update in the time step t is expressed as

$$\nabla f_{\{k_{(t)}^n\}} = \frac{\partial f_{\{k_{(t)}^n\}}}{\partial k} \tag{5}$$

Equation (4) is repeated n times to update the parameters and estimate the parameters for each time step.

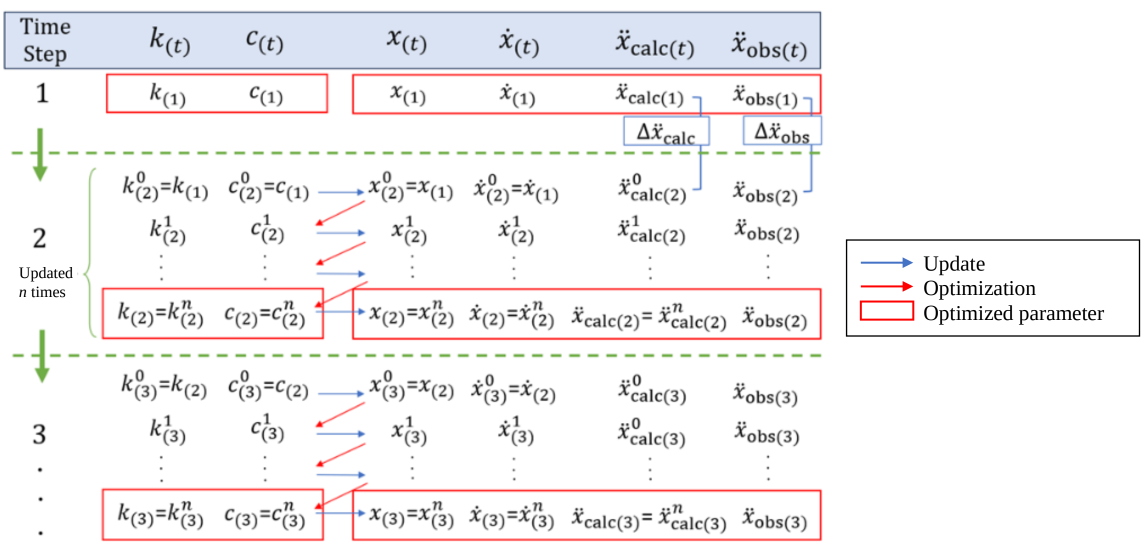


Figure 1. Conceptual diagram of the sequential parameter optimization method

VERIFICATION OF ESTIMATION ACCURACY BY NUMERICAL EXPERIMENTS

Table 1 shows the parameters of the analytical model used in the numerical experiments. In the numerical experiments, the seismic response analysis of a SDOF system shown in Figure 2 with the restoring force characteristics of the normal bilinear model is performed. The acceleration time history obtained from the analysis are used as the observed data. Parameter γ shown in table 1 is the stiffness reduction rate. the damping is proportional to the initial stiffness, and the damping ratio is 2 %. The input ground motion is the strong motion record observed by the Japan Meteorological Agency during the 1995 Hyogo-ken nanbu earthquake occurred in Japan.

Table 1: Parameter Specifications

Analysis model	m (ton)	k_0 (kN/m)	γ	T_0 (s)
①	3760	3713000	0.1	0.20
②	6400	1579000	0.1	0.40
③	10200	1114000	0.1	0.60
④	13300	821800	0.1	0.80
⑤	17200	680400	0.1	1.00
⑥	20000	547800	0.1	1.20
⑦	23900	481300	0.1	1.40
⑧	26600	410900	0.1	1.60
⑨	30600	327300	0.1	1.80
⑩	33300	328700	0.1	2.00

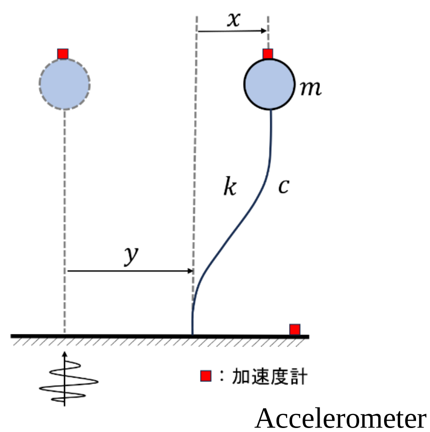


Figure 2. Analysis model

The proposed method is applied to the analytical models (3) and (8) to verify the estimation accuracy. The estimation results using the proposed method are shown in Figures 3. In analytical model (8), the estimated value corresponds to the change in the true value. On the other hand, in analytical model (3), the tangential stiffness of estimation result began to deviate from the true value around 7 s. In Figures 3(c), the estimated restoring force of analytical model (3) diverges in the middle of the iteration. This is caused by the fact that the parameter α, which is a constant, is not of the optimal for convergence due to the change in the objective function at each iteration, resulting in poor convergence and divergence.

Based on the above results, the next section discusses the optimal setting of the parameter α in accordance with changes in the objective function.

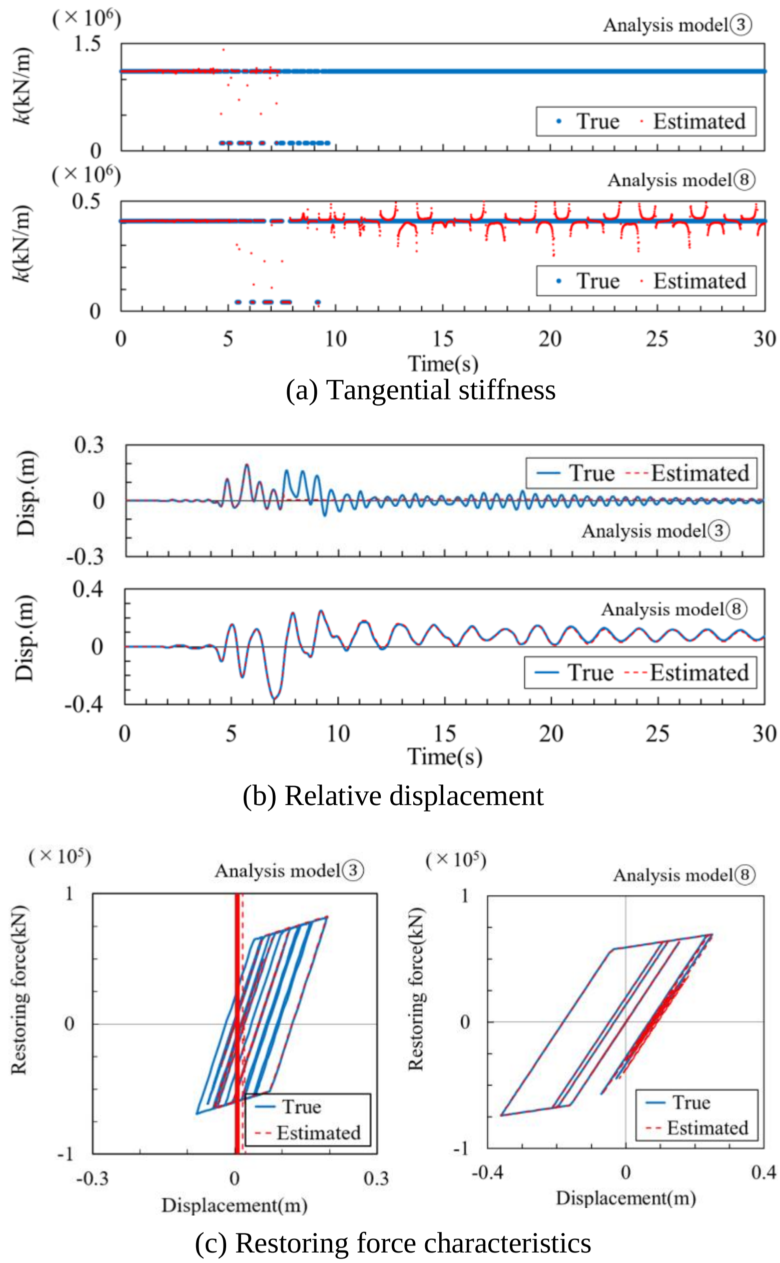


Figure 3. Estimation results

SETTING HYPERPARAMETERS

In this section, we examine the setting of the parameter α in accordance with changes in the objective function. Equation (1) is completed the square for stiffness $k_{(t)}^{n}$ as shown in the following equation.

$$f_{\left\{k_{(t)}^{n}\right\}} = \left[\frac{\Delta x_{(t)}^{n}}{m}\left\{k_{(t)}^{n} + \frac{c_{(t)}^{n}\Delta\dot{x}_{(t)}^{n} + m\Delta\ddot{x}_{\mathrm{obs}(t)}}{\Delta x_{(t)}^{n}}\right\}\right]^{2} \tag{6}$$

Where, the parameter that determines the shape of the objective function $f_{\left\{k_{(t)}^{n}\right\}}$ is shown in the following equation and is denoted as parameter $S_{(t)}^{n}$.

$$S_{(t)}^{n} = \left\{\frac{\Delta x_{(t)}^{n}}{m}\right\}^{2} \tag{7}$$

Using the parameter $S_{(t)}^{n}$, α is expressed as

$$\alpha_{(t)}^{n} = A^{\left|\log_{B} S_{(t)}^{n}\right|} \tag{8}$$

where A and B are constants, and the various restoring force characteristics can be estimated by parametric studies. The two indices, convergence speed and root mean square error (RMSE), are considered in the parametric study. The RMSE is calculated using the following standardized equation, since the parameters differ for each analytical model.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{t=0}^{N-1}\left\{\frac{k_{\mathrm{true}(t)} - k_{\mathrm{calc}(t)}}{k_{\mathrm{true}(t)}}\right\}^{2}} \tag{9}$$

where N is the total number of time steps, and $k_{\mathrm{true}(t)}$ and $k_{\mathrm{calc}(t)}$ are the true and estimated values of tangent stiffness at time step t, respectively.

The observation data are up sampled to 1000 Hz and the number of iterations is set to 1000. Figure 4 shows the convergence speed when the tangential stiffness is estimated for the analytical models (1) to (10) shown in Table 1 under 18 conditions: three conditions for the constant A and six conditions for B (see Table 3). The figure shows the convergence speed for each condition at the time (4.738 s) when the tangential stiffness of the analytical model (5) decreases. Convergence is fastest for the condition (A, B) = (10, 12).

Table 3: Conditions for consideration of parameter α

	Analysis conditions					
A	5		10		15	
B	2	5	10	12	15	20

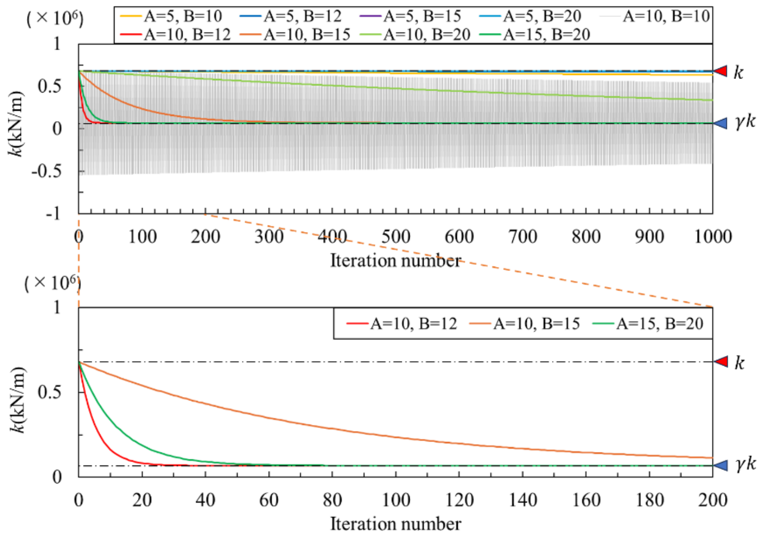


Figure 4. Convergence speed

Figure 5 shows the RMSE. The RMSE is relatively small for the conditions (A, B) = (10, 12), (10, 15), and (15, 20). Thus, the condition (A, B) = (10, 12) as the optimal parameter, where the convergence speed is the fastest and the RMSE is the smallest.

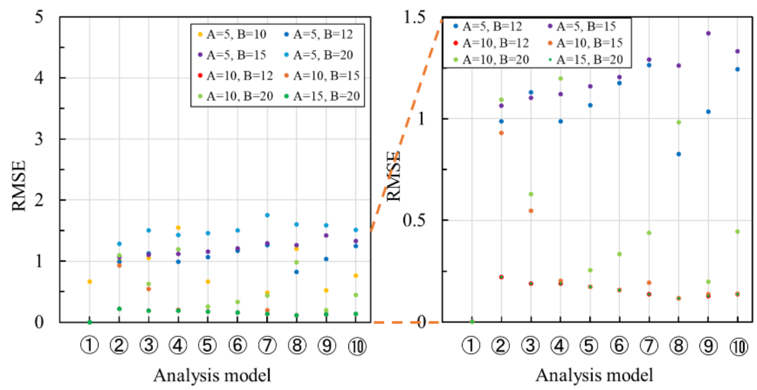


Figure 5. RMSE

ESTIMATION RESULTS USING THE PROPOSED METHOD

With the parameter α considered in the previous section, the proposed method is applied to the analytical models (11) to (20) with the initial natural period of 0.1 to 1.9 s shown in Table 4 to verify the estimation accuracy.

Table 4: Parameter Specifications

Analysis model	m (ton)	k_0 (kN/m)	γ	T_0 (s)
⑪	1730	6879000	0.1	0.10
⑫	5090	2235000	0.1	0.30
⑬	7700	1216000	0.1	0.50
⑭	12600	1015000	0.1	0.70
⑮	16400	797900	0.1	0.90
⑯	19000	618700	0.1	1.10
⑰	22730	531000	0.1	1.30
⑱	25300	444300	0.1	1.50
⑲	29100	397400	0.1	1.70
⑳	31690	346500	0.1	1.90

Figure 6 shows the RMSE of the tangential stiffness calculated by the equation (9). Figure 6 shows that the RMSEs of the analytical models (11) to (20) are all less than 0.25 and can be estimated with high accuracy.

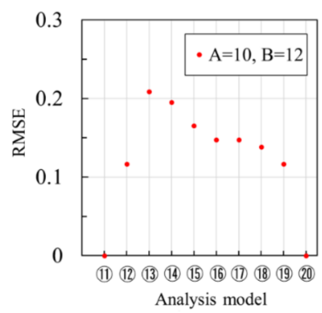


Figure 6. RMSE of tangential stiffness

Figures 7 and 8 show the relationship of the maximum relative displacement and the maximum restoring force between the true value and the estimated value. The estimated values correspond well to the true values.

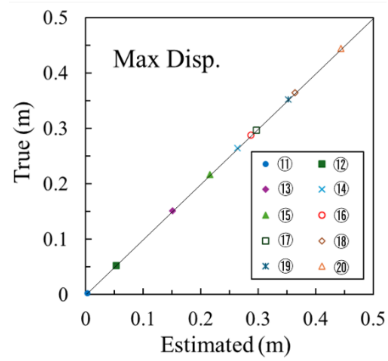


Figure 7. Maximum Response Displacement

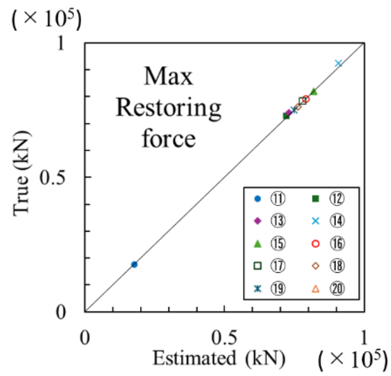


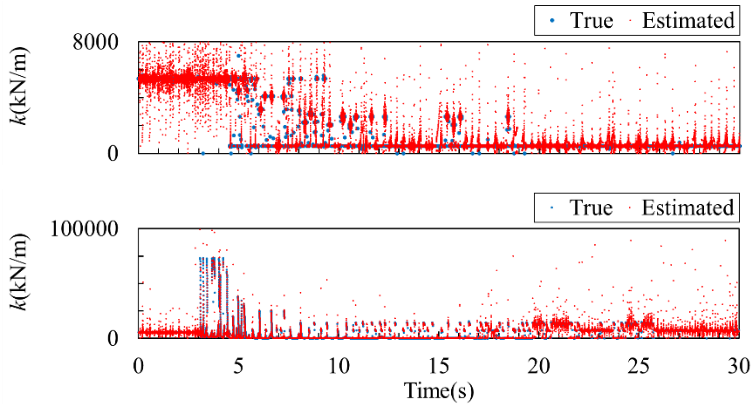
Figure 8. Maximum restoring force

Next, the tangential stiffness and other properties were estimated for an analytical model with a bilinear slip model and a normalized-characteristic-loop model (NCL model) (Tani, S. et al., 1972) that can reproduce slip behavior to verify the estimation accuracy. Table 5 shows the parameters of the two models.

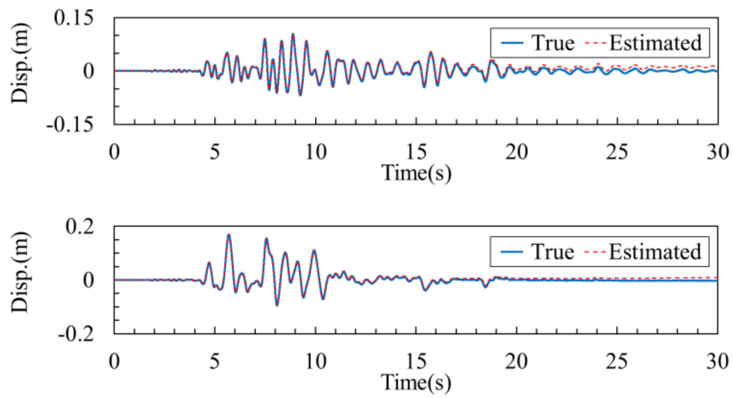
The estimation results are shown in Figure 9. In Figure 9(a), both models were able to follow changes in the true values and generally corresponded to them. In Figure 9(b), the amplitude, phase, and period are estimated with high accuracy. In Figure 9(c), the estimated values correspond well to the true values.

Table 5 Parameter Specifications

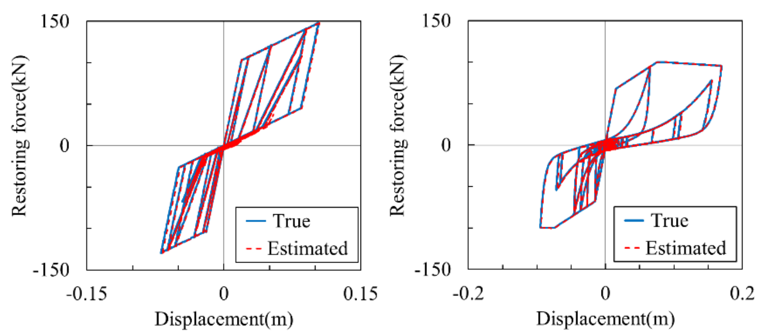
Restoring force characteristic	m (ton)	k_0 (kN/m)	T_0 (s)
Bilinear-slip model	9.3	5349	0.262
NCL model	9.3	5349	0.262



(a) Time history of tangential stiffness



(b) Time history of relative displacement



(c) Restoring force characteristics

Figure 13 Estimation results

In conclusion, by setting the parameter α according to the objective function, which changes from iteration to iteration, the tangential stiffness and other properties can be estimated with high accuracy even when the initial natural period and restoring force characteristics of the structure are different.

CONCLUSION

The tangential stiffness, relative displacement, and nonlinear restoring force characteristics were estimated using the sequential parameter optimization method proposed in this study. As a result, the proposed method was able to estimate tangential stiffness, relative displacement and restoring force characteristics with high accuracy. The proposed method can be applied to analytical models with various initial natural periods and restoring force characteristics by setting the parameter α according to changes in the objective function. The proposed method is effective for evaluating the seismic response of structures.

REFERENCES

Loh, C.-H. and Lin, H.-M. (1996), “Application of Off-line and On-line Identification Thecniques to Building Seismic Response Data,” Earthquake Engineering and Structural Dynamics, Vol. 25, pp. 269-290

Yoshimoto, R., Mita, A., and Okada, K. (2004), “Damage Detection of Base-isolated Buildings Using Multi-input Multi-output Subspace Identification,” Earthquake Engineering and Structural Dynamics, Vol. 34, pp. 307-324

Ishizaka, R. and Hida, T. (2022), “Nonlinear Time-Variant System Identification Using Particle Filters for Damage Assessment of Building Structures,” Bulletin of 17th Annual Conference of the Japan Association of Earthquake Engineering, F-12-6 (in Japanese)

Meiliang, W. and Andrew, S. (2007), “Application of the unscented Kalman filter for real-time nonlinear structural system identification,” Struct. Control Health Monit., 14, pp. 971-990.

Ihara, S. and Hida, T. (2023), “Identification of nonlinear dynamic characteristics during earthquakes by particle filters based on linear time-varying systems,” Summaries of technical papers of annual meeting of the Architectural Institute of Japan (in Japanese)

Tani, S., Nomura, S., Nagasaka, g., and Matsudaira, A. (1972), "Restoring Force Characteristics of Reinforced Concrete Aseismatic Elements (Part 1) -Restoring Force Characteristics and Modelization-," Transactions of the AIJ, Nol. 202, pp. 11-19 (in Japanese)