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Temporal variation in modal properties of a base-isolated building during an earthquake*

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Abstract: Temporal variation of dynamical modal properties of a base-isolated building is investigated using earthquake records in the building. A batch processing least-squares estimation method is applied to segment-wise time-series data. To construct an input-output system, an auto-regressive model with exogenous input (ARX) of second-order including a forgetting coefficient as a weighting coefficient is used for the estimation of modal parameters. The fundamental and second natural frequencies and the damping ratios of the fundamental and second natural modes of the base-isolated building are identified in the time domain. The identified results are consistent with the results obtained from the micro-tremor vibration data, forced-vibration test data and earthquake records in the present base-isolated building in the case of taking into account the amplitude-dependency of the isolators and viscous dampers. It is finally pointed out that several factors, e.g., amplitude dependency of the isolator and damper system and special characteristics of the series-type viscous damper system, may be related complicatedly with the temporal variation in modal properties of the above-mentioned system.

Key words: System identification, Shear building model, Modal parameters, Batch processing least-squares estimation method, Forgetting coefficient, Auto-regressive model with exogenous input (ARX) model
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1 Introduction

There are many base-isolated buildings in Japan after Hyogoken-Nambu earthquake (1995). However, it does not seem that the instrumentation of earthquake records at those base-isolated buildings is sufficient enough to demonstrate the validity and reliability of the design methods for base-isolated buildings. For this reason, a detailed instrumentation of earthquake records has been implemented by the present authors in Kyoto University since 1997.

System identification (SI) techniques which boast a long history played important roles in identifying gaps between the constructed structural systems and their design models and in health monitoring for damage detection (Hart and Yao, 1977; Beck and Jennings, 1980; Hoshiya and Saito, 1984; Agbabian *et al*., 1991; Koh *et al*., 1991; Yao and Natke, 1994; Ghanem and Shinozuka, 1995; Hjelmstad *et al*., 1995; Shinozuka and Ghanem, 1995; Doebling *et al*., 1996; Hjelmstad, 1996; Masri *et al*., 1996; Housner, 1997; Herrmann and Pradlwarter, 1998; Kitada, 1998). Much research has been performed so far in SI, in which modal-parameter SI and physical-parameter SI are two major branches (Hart and Yao, 1977). The modal-parameter SI as believed to be appropriate for identifying the overall mechanical properties of a structural system, exhibits stable characteristics in implementation. While the physical-parameter SI is regarded to be important from different viewpoints, e.g., enhancement of reliability in active controlled structures (Housner, 1997) or base-isolated structures,

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its development is limited because of the requirement of multiple measurements or the necessity of complicated manipulation. A mixed approach is often used in which physical parameters are identified from the modal parameters obtained by the modal-parameter SI. However, a sufficient number of modal parameters must be obtained for the unique and accurate identification of the physical parameters. This requirement cannot be satisfied in most cases.

Although the importance of damping in the seismic-resistant design of buildings is well recognized (Hart and Vasudevan, 1975), its identification techniques do not appear to be developed sufficiently. Especially the identification techniques for physical parameters, i.e., viscous damping coefficients and material damping ratios, are not fully developed compared to those for modal damping (Davenport and Hill-Carroll, 1986; Kareem and Gurley, 1996; Lus *et al*., 1999; Stewart *et al*., 1999; Satake *et al*., 2003). To overcome this difficulty, the present authors developed some useful physical-parameter SI methods (Takewaki and Nakamura, 2000; 2005, Yoshitomi and Takewaki, 2009).

In this paper, temporal variation in modal properties of a base-isolated building is investigated using earthquake records in the building. An auto-regressive model with exogenous input (ARX) model of second-order including a forgetting coefficient as a weighting coefficient is used for estimating the modal parameters of the system. The fundamental and second natural frequencies and the damping ratios of the fundamental and the second natural modes are identified in the time domain. Several factors, e.g., amplitude dependency of the isolator and damper system and special characteristics of the series-type viscous damper system, may be related with the temporal variation in modal properties of the above-mentioned system. It will also be shown that the micro-tremor vibration data, forced-vibration test data and earthquake records in the present base-isolated building provide consistent results on amplitude-dependency of the isolators and viscous dampers.

2 System identification method

A batch processing least-squares estimation method (Mendel, 1995) is applied to segment-wise time-series data. It is assumed that the base-isolated building treated in this study can be described by an ARX model as expressed by

$$A(q)y(k)=B(q)u(k)+w(k), \tag{1}$$

where $u(k)$ and $y(k)$ are the input and output sequences respectively, and $w(k)$ is a white noise signal. $A(q)$ and $B(q)$, the polynomials including the auto-regressive (AR) and moving-average (MA) coefficients $\{a_i\}$ and $\{b_i\}$ respectively, are defined by

$$A(q)=1+a_1q^{-1}+a_2q^{-2}\cdots+a_{n_a}q^{-n_a}, \tag{2a}$$

$$B(q)=b_1q^{-1}+b_2q^{-2}\cdots+b_{n_b}q^{-n_b}, \tag{2b}$$

where q^{-j} as the back-ward shift operator is defined by $q^{-j}y(k)=y(k-j)$, and n_a and n_b are the orders of the output and input of the system, respectively.

The AR and MA coefficients $\{a_i\}$, $\{b_i\}$ in Eqs. (2a) and (2b) can be evaluated by the input and output sequences $u(k)$ and $y(k)$ recorded in the actual building. The scheme determining these coefficients will be explained later on.

The modal parameters are assumed to be estimated as

$$\boldsymbol{\theta}(N)=\boldsymbol{R}(N)^{-1}\boldsymbol{f}(N), \tag{3}$$

where $\boldsymbol{\theta}(N)$, $\boldsymbol{R}(N)$ and $\boldsymbol{f}(N)$ can be defined by

$$\boldsymbol{\theta}(N)=[a_1,a_2,\ldots,a_{n_a},b_1,b_2,\ldots,b_{n_b}]^{\mathrm{T}}, \tag{4a}$$

$$\boldsymbol{R}(N)=\frac{1}{N}\sum_{k=1}^{N}\lambda^{N-k}\boldsymbol{\varphi}(k)\boldsymbol{\varphi}^{\mathrm{T}}(k), \tag{4b}$$

$$\boldsymbol{f}(N)=\frac{1}{N}\sum_{k=1}^{N}\lambda^{N-k}y(k)\boldsymbol{\varphi}(k), \tag{4c}$$

where λ expresses a forgetting coefficient for the better representation of stochastic parameter estimate and $\boldsymbol{\varphi}(k)$ is given by

$$\begin{aligned}\boldsymbol{\varphi}(k)=[&-y(k-1),-y(k-2),\ldots,-y(k-n_a),\\&u(k-1),u(k-2),\ldots,u(k-n_b)]^{\mathrm{T}}.\end{aligned} \tag{5}$$

For this ARX model, the natural frequencies f_j and damping ratios ξ_j are evaluated as the modulus p_j and the arguments ξ_j of the poles of the polynomial equation including the AR and MA coefficients by (Safak, 1989)

$$f_j = \frac{-\ln|p_j|}{2\pi\xi_j\Delta t}, \tag{6}$$

$$\xi_j = \frac{-\ln|p_j|}{[\arg^2(p_j) + (\ln|p_j|)^2]^{1/2}}, \tag{7}$$

where Δt is the sampling interval.

Fig. 1 shows the conceptual diagram of the SI method used in this study. A time segment of 5 s will be moved sequentially for enabling the temporal identification of modal parameters.

Based on Takewaki and Nakamura (2000; 2005), the fundamental dynamical properties of this base-isolated building have been made clear to some extent. Analyzing recorded motions by a band-pass filter around the natural frequencies enabled one to determine the order of the ARX model as the second order.

The above procedure has been implemented for each time segment, and our SI has been conducted for the fundamental and second natural frequencies and the damping ratios of the fundamental and second natural modes.

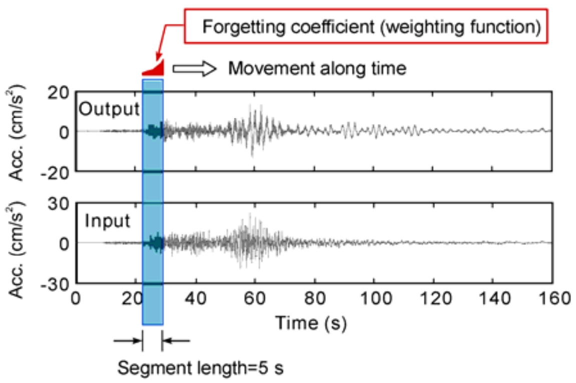


Fig. 1 Conceptual diagram of the system identification

3 Observation of earthquake records in base-isolated building

The observation of earthquake motions has been made in a base-isolated building on the Yoshida Campus of Kyoto University, Japan (Nakamura *et al*., 1998; Nakamura and Takewaki, 2002; 2005; Takewaki and Nakamura, 2000; 2005). The overview of the building and the accelerometer locations are shown in Fig. 2. This building is a three-story reinforced concrete building with basement, and the base-isolation (BI) system is installed under the basement. The BI system consists of 17 natural rubber bearings and 14 viscous dampers. The viscous damper system includes a viscous damper with butanoic-oil for earthquake motions and a viscous damper with silicon-oil for small vibrations in series. Several earthquake records are utilized (Table 1).

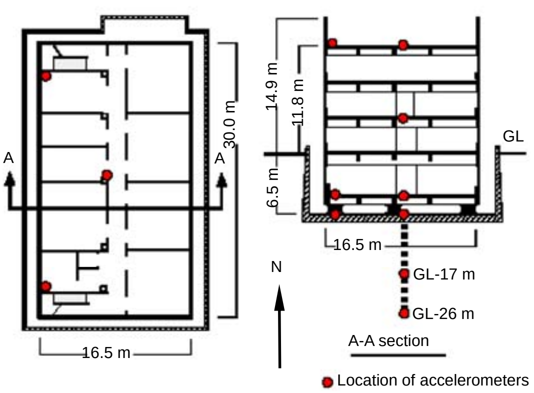
Figs. 3a and 3b show the relations of the fundamental natural period and the lowest-mode damping ratio with the deformation amplitude in the BI story (Nakamura *et al*., 1998). The horizontal axis is the maximum deformation amplitude in the BI story. The micro-tremor vibration data, forced-vibration test data and the results obtained from earthquake records are plotted in Fig. 3. As can be observed, the fundamental natural period in EW direction is longer than that in NS direction and the fundamental natural period becomes longer for larger deformation amplitudes. This seemingly results from the amplitude-dependency of the isolator horizontal stiffness. Also, the damping ratio becomes larger for larger deformation amplitudes. However, it should be noted that the amplitude-dependency of the damping ratio includes the effect of the amplitude-dependency of the natural period.

Table 1 Earthquake data and maximum accelerations above and below base-isolation story

Date	Earthquake data				Maximum acceleration (cm/s^2)			
	Epicenter	Depth (km)	Magnitude	Earthquake intensity	Base NS	Base EW	B1F NS	B1F EW
1997. 3. 16	East of Aichi Pref.	39	5.8	2	8.09	3.45	2.24	4.38
1997. 6. 12	Southeast of Hyogo Pref.	20	3.9	1	2.78	3.16	3.18	1.66
1997. 6. 25	West of Shimane Pref.	12	6.1	0	1.00	0.84	1.26	0.51
1997. 9. 7	South of Kyoto Pref.	17	4.2	2	4.69	10.61	5.87	6.97
1998. 2. 6	South of Kyoto Pref.	10	3.8	0	1.98	1.78	1.74	2.46
1998. 2. 10	Hida District of Gifu Pref.	10	4.3	1	1.71	1.52	0.49	0.97

NS: north-south; EW: east-west; B1F: 1st basement floor

(a)



(b)

Fig. 2 (a) Overview of the base-isolated building and (b) accelerometer location on the Kyoto University campus

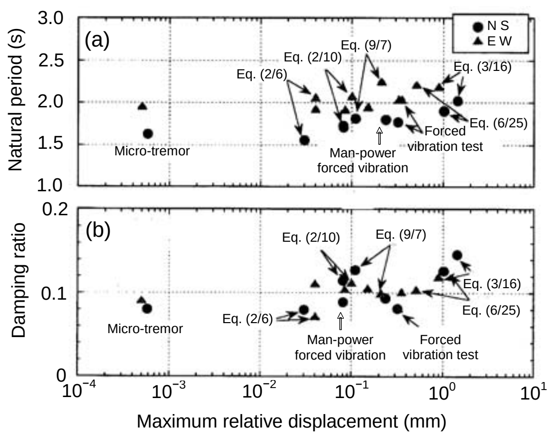


Fig. 3 (a) Relations of the fundamental natural period and (b) the lowest-mode damping ratio with the deformation amplitude in the base-isolation story (Nakamura *et al*., 1998)

Fig. 4 illustrates the relation of the damping coefficient of the viscous damper installed in the BI story with the deformation amplitude in the BI story. This figure is obtained from the equation:

$$c=2h\omega m,$$

where c is the damping coefficient, h is the lowest-mode damping ratio, ω is the fundamental natural circular frequency, and m is the total mass of building. The fundamental natural circular frequency and the lowest-mode damping ratio are used in this analysis. The forced-vibration test data and the results obtained from earthquake records are compatible with the results obtained from the viscous damper test.

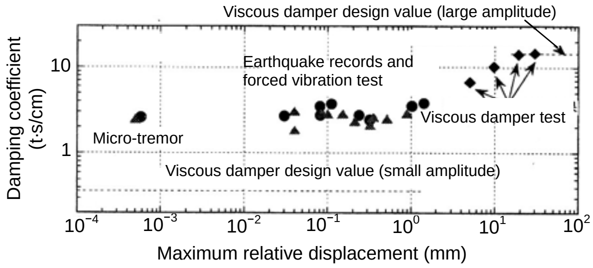


Fig. 4 Relation of the damping coefficient of the viscous damper installed in the base-isolation story with the deformation amplitude in the base-isolation story

4 Results of modal-parameter system identification

The records at the BI story and the second floor are used because the effect or component of the second vibration mode, according to Nakamura and Takewaki (2005), is small in the second floor. Fig. 5 shows the vibration-mode shapes of the fundamental and the second natural modes obtained from the forced vibration test. For the identification of the second mode, on the other hand, the records at the BI story (base) and the B1F (1st basement floor) are used.

Fig. 6 presents the acceleration records at the levels of 2F, B1F, BI floor (base) (Tokaido-oki Earthquake 2004. 9. 5 NS). It can be observed that the acceleration can be reduced remarkably in the building. Fig. 7 indicates the temporal variation of the interstory drift in the BI story. This figure is drawn to make clear the relation of modal properties with the amplitude of vibration. Fig. 8 shows the temporal variation of fundamental and the second natural frequencies (Tokaido-oki Earthquake 2004. 9. 5 NS). It is understood that, the fundamental natural frequency at the initial stage corresponds fairly well with the value (0.62–0.65 Hz) as obtained from the micro-tremor observation (Fig. 3) and becomes smaller in the beginning of the earthquake records (10–40 s). After 40 s, the fundamental natural frequency remains a reduced value. Similarly, the second natural frequency corresponds fairly well with the value (7.0 Hz) obtained from the micro-tremor observation. However, the reduction of the second natural frequency is not clear compared with the fundamental natural frequency. Fig. 9 illustrates the temporal variation of damping ratios of fundamental and second natural modes (Tokaido-oki Earthquake 2004. 9. 5 NS). Note that the initial damping ratio in the fundamental mode corresponds fairly well with the value (0.08) as obtained from the micro-tremor observation (Fig. 3). The damping ratio in the fundamental mode, after becoming a bit larger, reduces as the interstory drift in the BI story expands. It can be supposed that the amplitude dependency of the isolator and damper system and special characteristics of the series-type viscous damper system exert an influence on the temporal variation of the system modal properties.

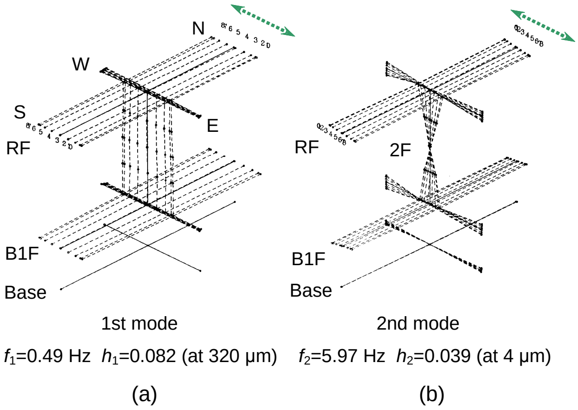


Fig. 5 Vibration-mode shapes of (a) the fundamental and (b) second natural modes obtained from the forced vibration test

f_1, f_2: 1st and 2nd natural frequencies; h_1, h_2: 1st and 2nd damping ratios; RF: roof; B1F: 1st basement floor

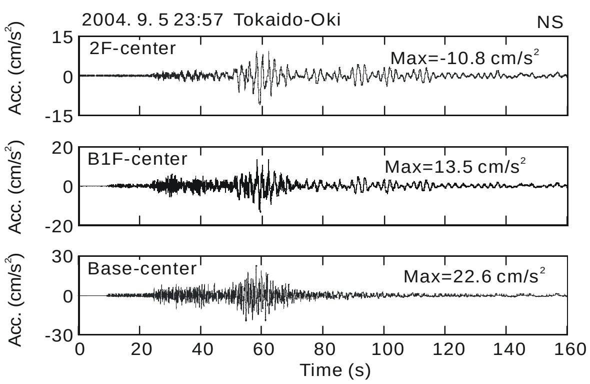


Fig. 6 Acceleration records at the levels of 2F, BF1, BI floor (Tokaido-oki Earthquake 2004. 9. 5 NS)

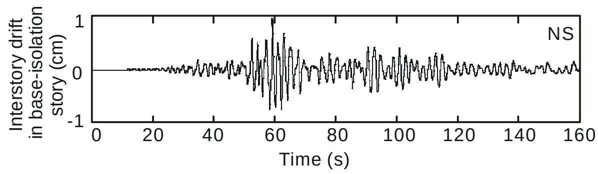


Fig. 7 Interstory drift in the base-isolation story (Tokaido-oki Earthquake 2004. 9. 5 NS)

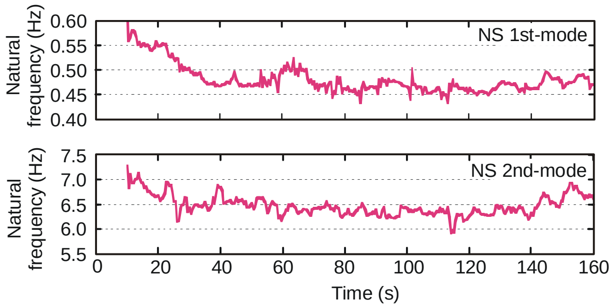


Fig. 8 Temporal variation of fundamental and the second natural frequencies (Tokaido-oki Earthquake 2004. 9. 5 NS)

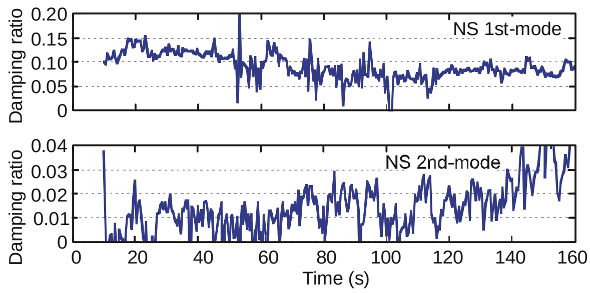


Fig. 9 Temporal variation of damping ratios of fundamental and second natural modes (Tokaido-oki Earthquake 2004. 9. 5 NS)

The corresponding figures for EW component are Figs. 10–13. A similar tendency can also be observed in EW components. The fundamental natural frequency at the initial stage corresponds fairly well with the value (0.51 Hz) as obtained from the micro-tremor observation (Fig. 3) and becomes smaller in the beginning of the earthquake records (10–50 s). The initial damping ratio in the fundamental mode also corresponds fairly well with the value (0.09) obtained from the micro-tremor observation shown in Fig. 3. The damping ratio in the fundamental mode, after becoming larger, decreases as the interstory drift in the BI story expands (after 60 s). Similarly, the second natural frequency corresponds fairly well with the value (5.9 Hz) obtained from the micro-tremor observation. However, the reduction of the second natural frequency is not clear compared with the fundamental natural frequency.

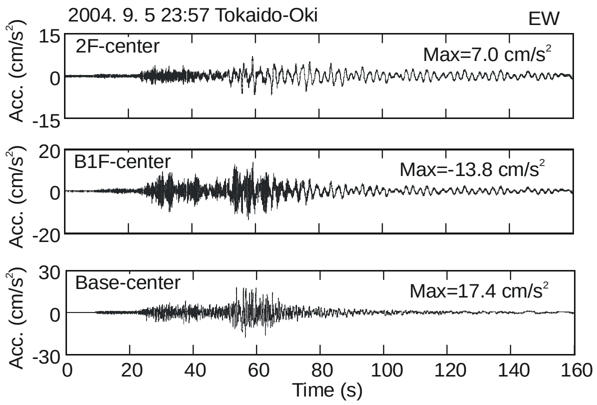


Fig. 10 Acceleration records at the levels of 2F, B1F, BI floor (Tokaido-oki Earthquake 2004. 9. 5 EW)

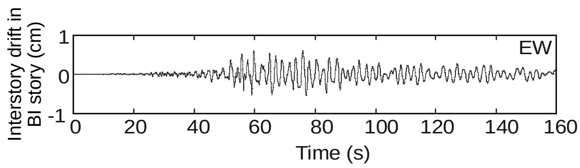


Fig. 11 Interstory drift in the base-isolation story (Tokaido-oki Earthquake 2004. 9. 5 EW)

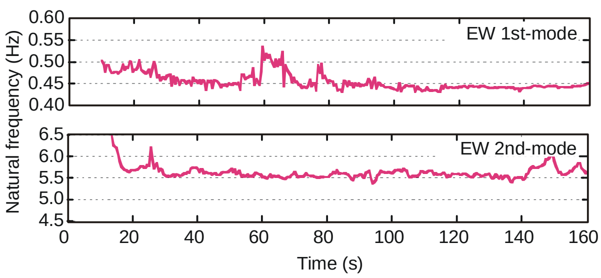


Fig. 12 Temporal variation of fundamental and the second natural frequencies (Tokaido-oki Earthquake 2004. 9. 5 EW)

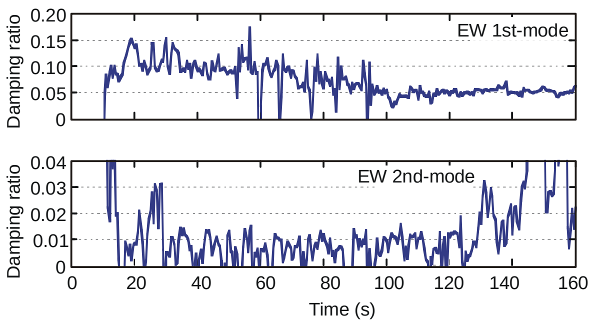


Fig. 13 Temporal variation of damping ratios of fundamental and the second natural modes (Tokaido-oki Earthquake 2004. 9. 5 EW)

Fig. 14 illustrates the velocity response spectra of the earthquake records (Tokaido-oki Earthquake 2004. 9. 5) at the base center. A long-period motion (around 10 s) exists in these earthquake records together with the motion around 1 s.

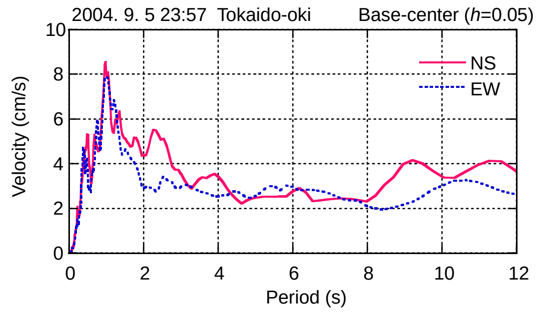


Fig. 14 Velocity response spectra of Tokaido-oki Earthquake 2004. 9. 5

To investigate the effect of earthquake types on the reliability of the present identification method, other earthquakes, Tottoriken-Seibu 2000 NS and the South of Kyoto Prefecture 2001 NS, are used. Fig. 15 shows the time variations of the interstory drift in the BI story, the fundamental natural frequency and the lowest-mode damping ratio for Tottoriken-Seibu 2000 NS, and Fig. 16 reports those for the south of Kyoto Prefecture 2001 NS. It can be observed that the properties similar to the results for the above-mentioned earthquake records can be found.

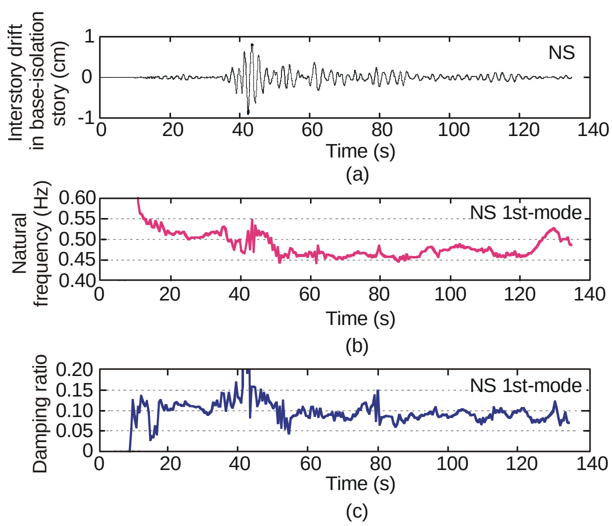


Fig. 15 Tottorikeneibu 2000 NS

(a) Interstory drift in the base-isolation story; (b) fundamental natural frequency; (c) the lowest-mode damping ratio

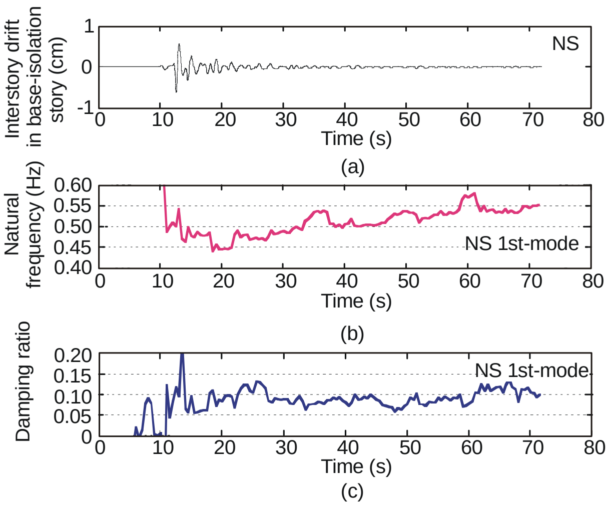


Fig. 16 South of Kyoto Prefecture 2001 NS
(a) Interstory drift in the base-isolation story; (b) fundamental natural frequency; (c) the lowest-mode damping ratio

It is possible to conclude that several factors, e.g., the amplitude dependency of the isolator and damper system and special characteristics of the series-type viscous damper system, are closely related with the temporal variation of the system modal properties (natural frequencies and modal damping ratios). The properties of damping systems, viscous or hysteretic (Nashif *et al.*, 1985; Inaudi and Kelly, 1995), should also be discussed carefully.

5 Conclusion

Dynamic properties of a base-isolated building are investigated using observed field data. The following observations are obtained:

(1) The combination of a batch processing least-squares estimation method and the ARX model representation of the input-output system is an efficient and reliable method of system identification of base-isolated buildings.

(2) The fundamental natural frequency and the damping ratio of the base-isolated building are time-dependent. This time-dependency is not a simple amplitude-dependent one, but seemingly dependent on the properties of earthquake ground motions and on the damping system used in this base-isolated building.

(3) The micro-tremor vibration data, forced-vibration test data and earthquake records in the present base-isolated building provide consistent results on amplitude-dependency of the isolators and viscous dampers.

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