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A COMPARISON BETWEEN NONLINEAR RESPONSES OF STRUCTURES SUBJECTED TO 1995 HYOGO-KEN-NANBU EARTHQUAKE AND 1993 KUSHIRO-OKI EARTHQUAKE

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ABSTRACT

A large number of structures suffered severe damage as a result of the Hyogo-ken-nanbu Earthquake which hit Kobe district on January 17, 1995. Strong ground motions having quite large peak accelerations were recorded at Kobe Marine Observatory. Records with similar values of peak acceleration were obtained at Kushiro Local Meteorological Observatory during the Kushiro-oki Earthquake which occurred on January 15, 1993. Although peak ground accelerations observed during these two earthquake events were relatively similar, in case of Kushiro-oki Earthquake no serious damage was observed. This paper aims at finding out the reason why there exists such a big difference between the amount of damage caused by these two earthquakes from the inelastic response analysis of simple vibrational systems excited by the acceleration records where peak values were observed.

KEYWORDS

earthquake damage; pseudo velocity response spectrum; inelastic response; ductility factor; normalized drift.

OBSERVED STRONG GROUND MOTIONS

Two large earthquakes rocked Japan within last two years moving the ground much more violently than expected. The first one, known as Kushiro-oki Earthquake, occurred on January 1993 and delivered peak ground acceleration of 711.4cm/s^2. The other one, known as Hyogo-ken-nanbu Earthquake, struck the Southern part of Hyogo prefecture on January 17, 1995, shaking the ground with a peak acceleration of 820.6cm/s^2. In Table 1 are summarized the important quantities related to the intensity of ground motion for three components of accelerograms recorded at Kobe Marine Observatory and Kushiro Local Meteorological Observatory, hereafter simply referred to as Kobe and Kushiro respectively.

Although peak accelerations for both records are similar to each other, peak velocities of Kobe are two to three times as high as those of Kushiro. The energy input given in the same table is defined to be (Housner, 1975)

$$E = \int_0^{t_d} \ddot{x}_g^{\,2}(t)dt \tag{1}$$

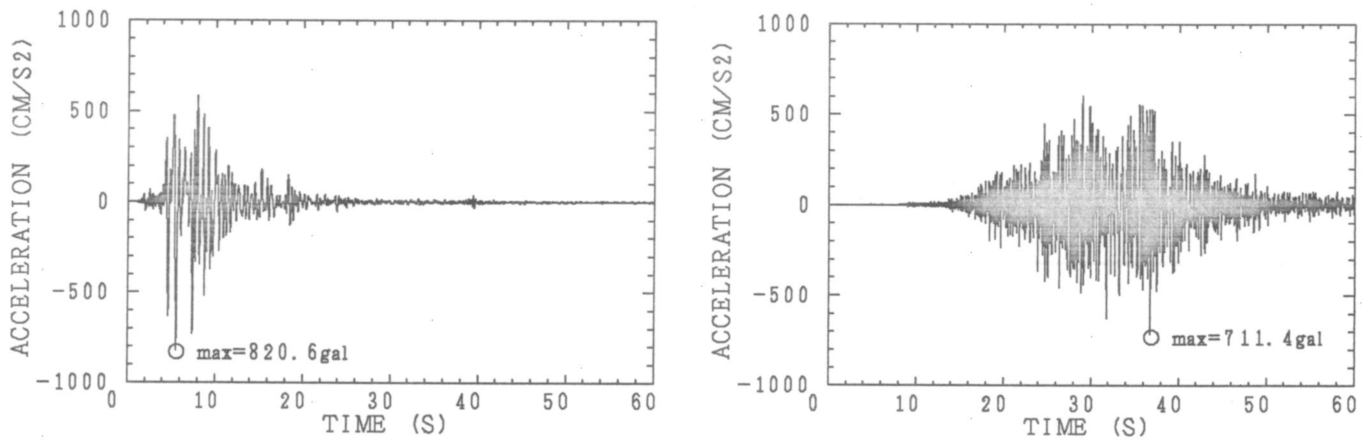
where $\ddot{x}_g(t)$ is the ground acceleration and t_d is its time duration. t_d is chosen large enough in order to avoid its effect on the energy input value. Since E depends not only on acceleration amplitude but also on time duration, energy input is sometimes a more appropriate index of ground motion intensity rather than peak acceleration itself. The values of E for Kushiro resulted to be about two times as high as those obtained in case of Kobe.

Table 1. Intensity of ground motion.

Site	**Component**	**Peak acc.** *cm/s²*	**Peak vel.** *cm/s*	**Energy input** *cm²/s³*	**Duration of principal motion**
Kobe	NS EW UD	820.6 619.2 333.3	92.6 76.0 40.9	5.3×10^5 3.4×10^5 1.2×10^5	around 15 seconds
Kushiro	N063E N153E UD	711.4 637.2 363.4	34.3 40.7 14.7	9.7×10^5 7.5×10^5 2.7×10^5	around 30 seconds

From two horizontal components of each record, the one having larger peak acceleration is used for analysis. Kobe NS and Kushiro N063E are selected from this standpoint. Both Kobe and Kushiro Observatories are located on small hills with height of 30m and have underlain soil deposits with thickness of around 15m. Those topographies and local soil conditions possibly affected the short period components of acceleration records especially. In this paper, however, original accelerograms are directly used in response analysis in order to avoid the inclusion of uncertainty caused by the modification of records due to the local soil condition effect. This problem is left for future study.

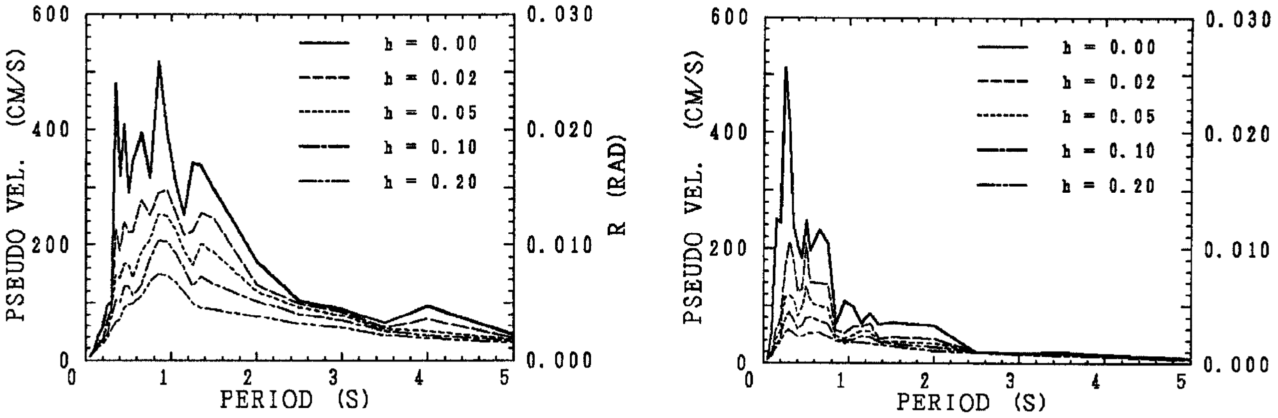
The two accelerograms used in analysis are displayed in Fig. 1(a) and (b). Pseudo velocity response spectra ${}_pS_V$ for two selected strong ground motions are shown in Fig. 2(a) and (b), where five different values are assigned to the damping ratio h.



(a) Kobe NS

(b) Kushiro N063E

Fig. 1. Accelerograms used in response analysis.



(a) Kobe NS

(b) Kushiro N063E

Fig. 2. Pseudo velocity response spectra.

In the short period range, spectral levels for both ground motions are similar to each other while in the period range longer than say 0.4s the spectral level of Kobe NS is much higher than that of Kushiro N063E.

The scale on the right hand side of the figure stands for the normalized drift R, which is defined as the ratio of maximum displacement response of the structure to its height H. This is estimated on the basis of the following process:

On average, the fundamental natural period of the building T(s) is related to its height H(cm) as

$$T = 2.5 \times 10^{-4} H \tag{2}$$

The average normalized drift R for a multi-mass system can be approximately estimated by

$$R \approx \frac{1.3 \cdot |x|_{\max}}{H} \tag{3}$$

where the coefficient 1.3 corresponds to the participation function at the top of the building in the fundamental mode of vibration. $|x|_{\max}$ is the maximum displacement response of the structure modeled as a single-mass system or the displacement response spectrum S_D in case of an elastic system. Since ${}_pS_V$ is equal to $(2\pi / T) \cdot S_D$, with the aid of eqs. (2) and (3) there is obtained

$$R \approx \frac{1.3 \cdot |x|_{\max}}{H} \approx \frac{1.3 \times 2.5 \times 10^{-4}}{T} \cdot \frac{T}{2\pi} \cdot {}_pS_V = 5.2 \times 10^{-5} {}_pS_V \tag{4}$$

where R and ${}_pS_V$ are in radian and cm / s, respectively.

This indicates that R is simply proportional to the pseudo velocity response spectrum ${}_pS_V$, with a proportional constant of around 1/20000 (s/cm).

NONLINEAR RESPONSE ANALYSIS

A structure is idealized by the mass-dashpot-spring system having single degree of freedom. A horizontal ground motion is applied to the system. Equation of motion is written as

$$\ddot{x} + 2h\omega\,\dot{x} + \frac{Q}{m} = -\ddot{x}_g(t) \tag{5}$$

where ω $(=2\pi/T)$ represents the natural angular frequency of the system in the elastic stage. Q and m stand for restoring force of spring and mass, respectively.

The restoring force characteristic is assumed as the sum of two hystereses, bilinear and slip. In the bilinear hysteresis the stiffness fully recovers at the unloading stage, whereas in the slip hysteresis the displacement progresses toward the last slip displacement when the restoring force becomes zero. The proper combination of the two hystereses can represent the great variety of hysteretic characteristics of structures ranging from ductile to brittle behavior. A parameter s, so-called "slip ratio" , is introduced. The contributions of bilinear and slip hysteresis to the total stiffness k and total strength Q_y are taken respectively as $(1-s)k$, $(1-s)Q_y$ and sk, sQ_y. Restoring force characteristics for three typical values of s are schematically illustrated in Fig.3(a),(b) and (c). Plastic stiffness for both hystereses is assumed to be zero.

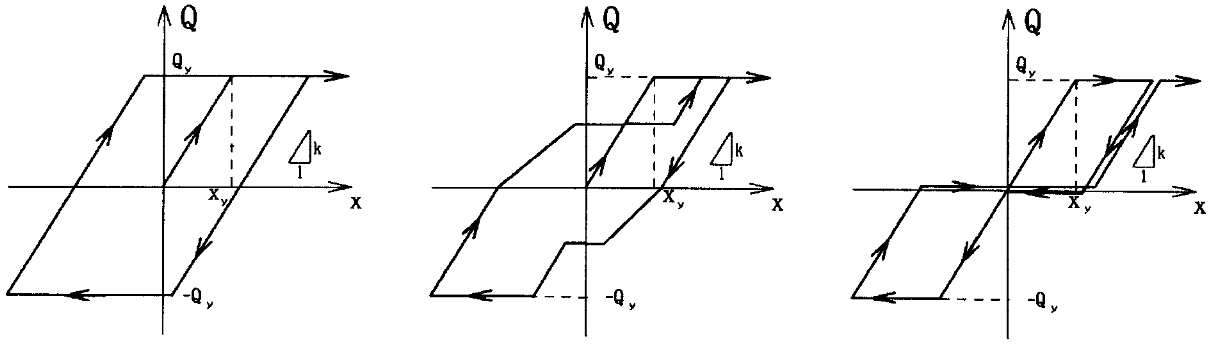
The attention is focused on ductility factor D and normalized drift R, as two of the most important indices which characterize the degree of structural damage. D is defined by

$$D = \frac{|x|_{\max}}{x_y} \tag{6}$$

where x_y is the yield displacement. R is determined from the combination of eqs. (2) and (3) as

$$R \approx \frac{1.3 \times 2.5 \times 10^{-4}}{T} \cdot |x|_{\max} = \frac{3.25 \times 10^{-4}}{T} \cdot |x|_{\max} \tag{7}$$

where T and $|x|_{\max}$ are in second and cm, respectively.



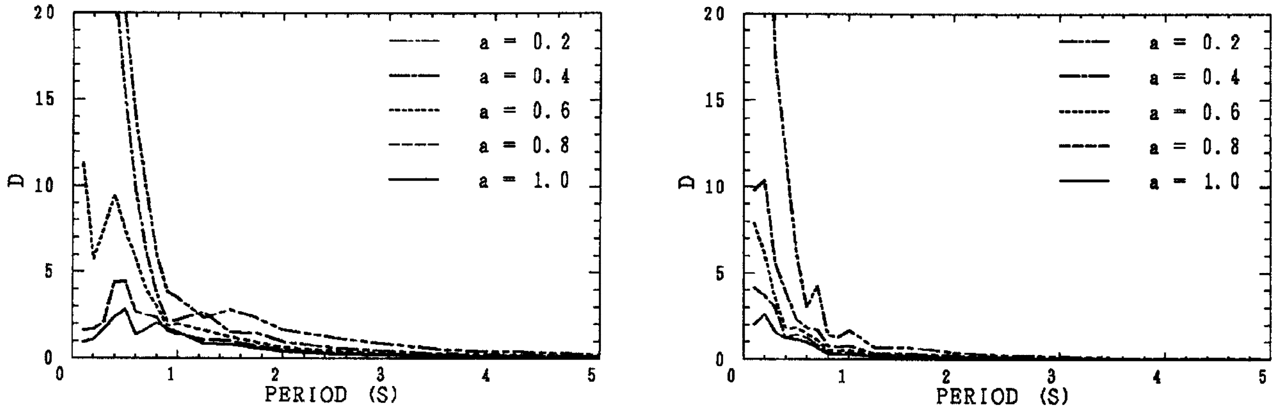
(a) $s = 0.0$ **(b)** $s = 0.5$ **(c)** $s = 1.0$

Fig. 3. Restoring force characteristics.

Response spectra for both indices, with parameters s and yield shear coefficient a (= Q_y/mg), are computed for two selected ground motions. The parameter s varies from 0.0 to 1.0 with an increment of 0.25, while a varies from 0.2 to 1.0 with an increment of 0.2. Damping ratio of the system is assumed to be 0.05.

ANALYSIS RESULTS

In order to examine the effect of strength of structure on ductility factor, ductility factor response spectra with the variable parameter a for two selected excitations are depicted in Fig. 4(a) and (b). These results correspond to $s = 0$. In the short period range, say shorter than 0.3s, D values exceed 4 for both input motions, providing that a is less than 0.8.



(a) Kobe NS

(b) Kushiro N063E

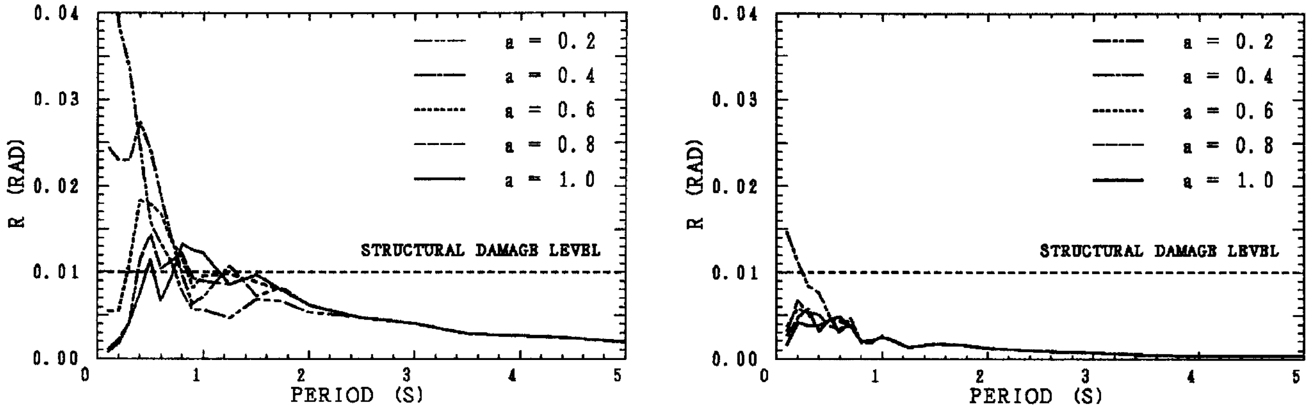
Fig. 4. Ductility factor response spectra.

From the viewpoint of structural damage, it seems that the story drift is a more appropriate index than the ductility factor. On average, the experimental results have shown that the normalized drift is correlated to the degree of structural damage in the way presented in Table 2, although this relation depends on many parameters such as structural system, component, material and so on. For this reason the normalized drift response spectra computed from eq. (7) are displayed in Fig. 5(a) and (b), where a is again taken as a variable parameter and s is fixed on zero. The drift responses due to Kobe NS are much higher than those due to Kushiro N063E. In the former case moderate to severe damage results in buildings having periods shorter than 0.8s, unless a is high enough. On the other hand, in case of Kushiro N063E R remains below the structural damage level for any value of a, even in the short period range.

Table 2. Relation between R and degree of damage.

R	Degree of damage
0.005	No or slight damage
0.01	Moderate damage
0.02	Severe damage
0.04	Collapse

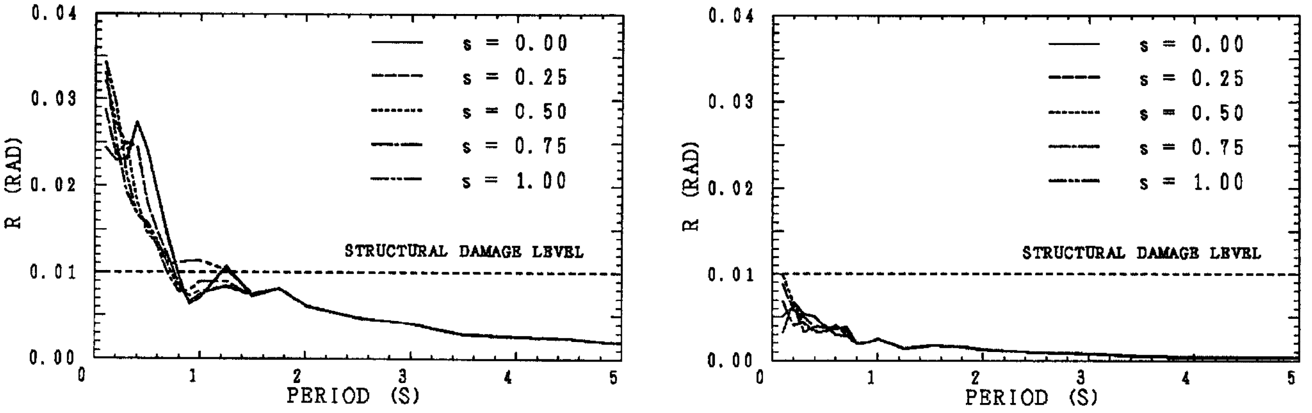
The effect of slip ratio *s* on the normalized drift is illustrated in Fig. 6(a) and (b), where *a* is fixed now on 0.4. The responses due to Kobe NS depend somewhat on *s*, while in case of Kushiro N063E input motion, *s* does not play any important role.



(a) Kobe NS

(b) Kushiro N063E

Fig. 5. Normalized drift response spectra.

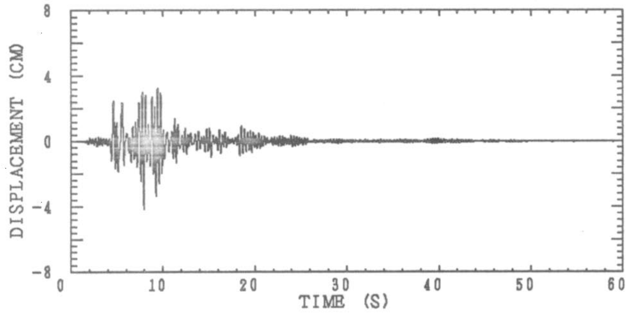


(a) Kobe NS

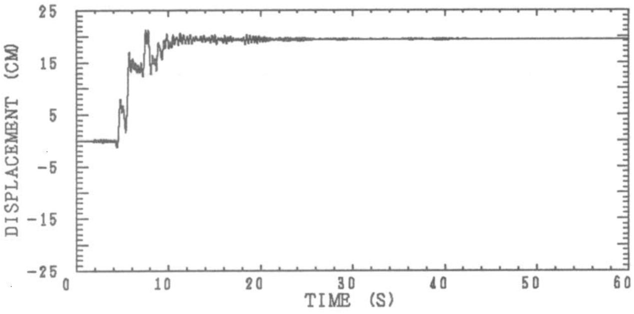
(b) Kushiro N063E

Fig. 6. Normalized drift response spectra (a=0.4).

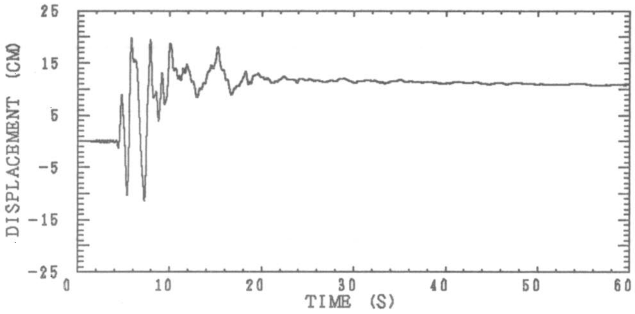
The elastic pseudo velocity response spectra (Fig. 2) show that Kobe NS is a wide-band process with high spectral values extending to long period range, while Kushiro N063E is a narrow band process where the high spectral value concentrates exclusively on the relatively short period range. This fact produces the big difference between inelastic responses due to two selected excitations. In case of Kobe NS input motion, the response depends somewhat on *s*, and *R* results to be much greater than that of Kushiro N063E, where *R* remains below the level of structural damage regardless of *s* even in the short period range, unless *a* is quite low. For a visible illustration of this phenomenon, displacement time histories for a system having the natural period of 0.3s are shown in Fig. 7 and Fig. 8 as typical examples. In the elastic responses (Fig. 7(a) and Fig. 8(a)) both time histories are in similar appearance, while in the inelastic responses (Fig. 7(b), (c) and Fig. 8(b), (c)) remarkable differences between respective cases are clearly observed.



(a) $a=\infty$ *(elastic)*

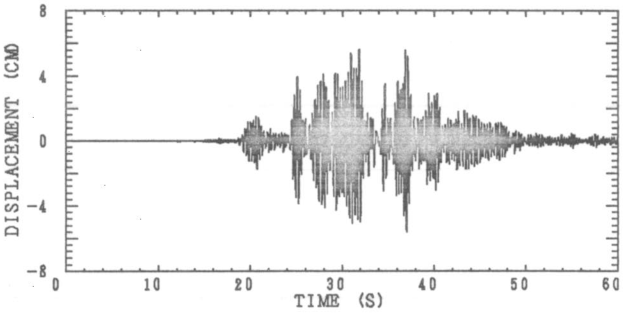


(b) $a=0.4$ *and* $s=0$

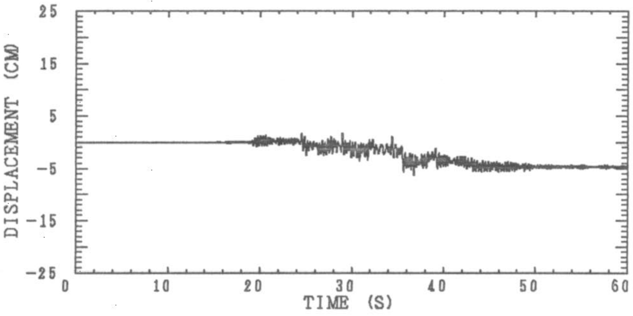


(c) $a=0.4$ *and* $s=1$

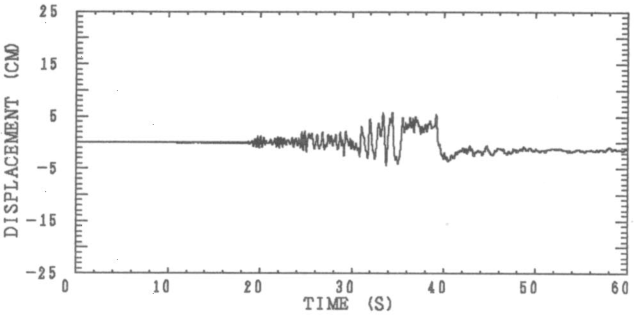
Fig. 7 Displacement time histories (Kobe NS).



(a) $a=\infty$ *(elastic)*



(b) $a=0.4$ *and* $s=0$



(c) $a=0.4$ *and* $s=1$

Fig. 8 Displacement time histories (Kushiro N063E).

CONCLUSION

Above presented results of nonlinear response due to two selected strong ground motions recorded during two earthquakes explain on the whole the reason why the Hyogo-ken-nanbu Earthquake brought about severe damage of structures, while the damage caused by Kushiro-oki Earthquake was only slight.

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