Relevance of earthquake ground motion characteristics with damage of reinforced concrete structures

Wenliuhan.Heisha[1]

[1] *Professor, EERTC , Guangzhou University, Guangzhou. China*
[1] *Chief engineer, Dept. of R and D, AS CO.LTD, Tokyo, Japan*
Email: WLH-GD@14wcee.org, wen.liuhan@ a-sys.co.jp

ABSTRACT :

One of the most important decisions in carrying out proper design is to select a design earthquake that adequately represents the ground motion expected at a particular site and in particular the motion that would drive the structure to its critical response, resulting in the highest damage potential. From the disasters of Off Tokachi Earthquake 1968 and Kobe Earthquake 1995, it is considered that the time duration plays an important role on the damage potential of the earthquake and pointed out that the behavior of structures is dominated by the characteristics of earthquake ground motions. The purpose of this study was to investigate the differences in the inelastic dynamic behavior of reinforced concrete structures subjected to earthquake ground motions with different characteristics. The variations were earthquake ground motions with different characteristics to ascertain damage potential of earthquake ground motions reflecting regional conditions such as oceanic earthquake and near fault earthquake. The study was also to develop techniques to estimate structural displacements which are an index of structural damage during strong earthquake ground motions. Damaging potential of earthquake ground motions, and hysteretic energy characteristics of reinforce concrete structure were evaluated by investigation of momentary energy response behavior, which is related to displacement behavior of structure, the maximum displacement response was estimated by energy method. Estimating method of maximum displacement of reinforce concrete structures during strong ground earthquakes was verified also by comparing with FEM method.

KEYWORDS: Earthquake, Damage potential, Hysteretic energy, Energy response

1. INTRDUCTION

Generally, the potential energy of the earthquake motion is often valued by maximum acceleration and maximum velocity. Many earthquake motions with huge acceleration were recorded which were not seen until recently. The potential energy of the earthquake motion and relation of damage of the structure are again argued. Table 1 show the earthquake list which occurred after Kobe earthquake in Japan. The maximum acceleration of chuoetu earthquake in 2004 reached 1676 cm/s2; it is larger than Kobe earthquake in 1995. And maximum velocity of chuoetu earthquake in 2004 reached 146 cm/s, it is larger than Kobe earthquake in 1995. Damage due to the chuoetu earthquake in 2004 was less than Kobe earthquake; it is because of the development of seismic design method based on the classes of Kobe earthquake, also the investigation of the damage potential difference of recorded earthquake motions. In order to discuss the difference of recorded earthquake ground motions, in this paper, the input variations were input motions with different characteristics to ascertain damage potential of earthquake ground motions reflecting regional conditions such as oceanic (interpolate) earthquake and near fault (intraplate) earthquake. The study was also to develop techniques to estimate structural displacements which are an index of structural damage during strong earthquakes, and design algorithm that incorporates these techniques. Damaging potential of ground motion, and hysteretic energy characteristics of reinforce concrete structure were evaluated by investigation of momentary energy response behavior, which is related to displacement behavior of structure, the maximum displacement response was estimated by energy method.

2. ENERGY RESPONSE

2.1 Introduction

The damage potential of earthquake ground motion is not only by maximum responses but also by cyclic load effect to structure, and that is possible to estimate the maximum response displacement by using energy response. It is suitable index for discussing the differences of damaging potential of different types of earthquake as used in seismic design of bridge in Japan.

Table 1.1 Earthquake list

Earthquake	Year	Direction	Maximum acceleration cm/s^2	Maximum Velocity cm/s
Kobe	1995.01.17	NS	818.0	96.5
Totori	2000.10.06	NS	923.9	127.1
Miyagioki	2003.05.23	NS	887.9	17.2
Tokachioki	2003.09.26	EW	969.8	46.7
Chuoetu	2004.10.23	EW	1676.0	146.0
Notohanto	2007.03.25	EW	849.0	50.5
Chuoetu	2007.07.16	EW	878.6	105.0

2.2 Derivation of Energy Equation for A SDOF system

Given a viscous damped SDOF (single degree of freedom) system subjected to a horizontal earthquake ground motion $\ddot{x}_g$, the equation of motion can be written as:

$$m\ddot{x} + c\dot{x} + F_s = -m\ddot{x}_g \tag{2.1}$$

Where:

m: mass; F_s : Restoring force; x : Relative displacement; $\ddot{x}_g$: Earthquake ground motion

Integrating Eqn.(2.1) with respect to x form the time of start of the motion gives:

$$\int_0^T m\ddot{x}\dot{x}dt + \int_0^T c\dot{x}\dot{x}dt + \int_0^T F_s\dot{x}dt = -\int_0^T m\ddot{x}_g\dot{x}dt \tag{2.2}$$

Further, Eqn. (2.2) can be written as:

$$\int_0^T c\dot{x}\dot{x}dt + \int_0^T F_s\dot{x}dt = -\int_0^T m\ddot{x}_g\dot{x}dt - \int_0^T m\ddot{x}\dot{x}dt \tag{2.3}$$

The first term of left-hand of Eqn.(2-3) is the viscous-damping energy E_D. The second term of the left-hand of Eqn. (2-3) is the dissipated energy E_H, the first term of right-hand of Eqn. (2-3) is the energy input to the system E_I. It is called input energy, because it is formulated in term of the ground acceleration. The second term of the right-hand of Eqn. (2-3) is the kinetic energy of the system E_V, so-called because it is formulated in term of the absolute velocity. Using these definitions, Eqn. (2-3) can be written as in the form:

$$E_D + E_H = E_I + E_V \tag{2.4}$$

Several points can be noted about Eqn. (2-4). If the term is integrated over the entire duration T of the earthquake and until the structure comes to rest, then E_V is zero. In this case, the total input energy E_I is equated by the internal energy dissipated (damping) of the system, E_D and E_H.

$$E_D = \int_0^T c\dot{x}\dot{x}dt \tag{2.5}$$

$$E_H = \int_0^T F_s \dot{x} dt \tag{2.6}$$

$$E_I = \int_0^T m\ddot{x}_g \dot{x} dt \tag{2.7}$$

$$E_V = \int_0^T m\ddot{x}\dot{x} dt \tag{2.8}$$

2.3 definition of Maximum Momentary Input Energy

Under earthquake loading, a reinforced concrete structure is weakened or damaged by a combination of stress reversals and high stress excursions. Consequently, any damage criterion should include not only the maximum response, but also the effect of repeated cyclic loading. For reflecting the damaging potential, the energy time histories are not enough. Here momentary input energy ΔE is defined to indicate the intensity of energy input to structures. ΔE is defined by increment of dissipated energy ($E_D + E_H$) during Δt that is interval time of $E_V = 0$ where $\dot{x}$ becomes zero. As shown in Figure 2.1, Δt is a half cycle of hysteretic loop and it changes for each cycle.

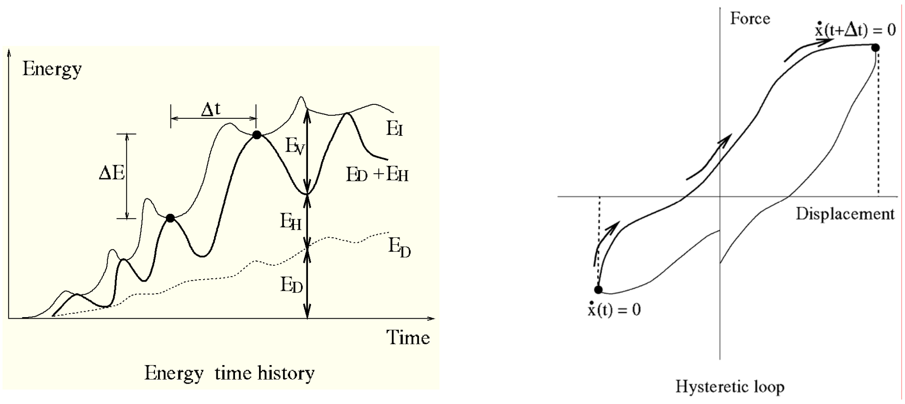

Figure 2.1 Energy time history and hysteretic loop

$$\Delta E = \int_t^{t+\Delta t} c\dot{x}\dot{x} dt + \int_t^{t+\Delta t} F_s \dot{x} dt = -\int_t^{t+\Delta t} m\ddot{x}_g \dot{x} dt \tag{2.9}$$

The maximum value of momentary input energy ΔE is defined as $\Delta E_{\max}$. It is pointed out that the maximum displacement response occurs just after $\Delta E_{\max}$ was inputted.

3. INPUT EARTHQUAKE MOTIONS

For investigating the effect of time duration on the damage potential of different simulated input motions, earthquake ground motions should be reflect real characteristics of target input motions. For reflecting the damage potential of real earthquake motion, it is necessary to input one large intensity motion in one time but not like shaking table test, which inputted in an increasing intensity. From these circumstances, the proposed model above was used to evaluate the effect of time duration on the damage potential of target simulated input motions. The earthquake motions used for seismic design of bridge of Japan's design code TYPE I and TYPE II were used to these analyses and named as CASE-L and CASE-S respectively. Figure 3-1 shows the time histories of typical earthquake motions.

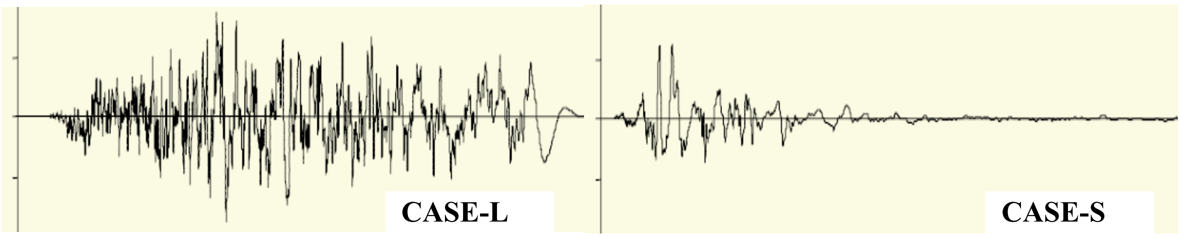

Figure 3-1 Time histories of typical earthquake motions

4. PARAMETERS OF REINFORCED CONCRETE PIER AND NONLIEAR ANALYSIS RESULT

In order to compare with dynamic nonlinear analysis result of reinforce concrete structure; reinforced concrete pier designed by using Japanese seismic design code was selected. Table 4.1 and 4.2 show the parameters and nonlinear time history analysis results.

Table 4.1 Analysis parameter

	Type I	Type II
Yielding Capacity Py(kN)	5655.8	5655.8
Yielding Displacement Dy(m)	0.044	0.044

Table 4.2 Analysis result

Input motion	Maximum displacement of Pier (m)
Type I-1	0.054
Type II-1	0.210
Type I-2	0.1238
Type II-2	0.215

5 PREDICTION OF MAXIMUM RESPONSE DISPLACEMENT

5. 1 Prediction Method

Based on the energy response, it is possible to estimate the maximum displacement of a structure to an earthquake. This is a simplified method that can estimate the maximum displacement of a nonlinear system without taking time history analysis.

5. 2 $\Delta E_{\max}$ (Maximum Momentary Input Energy)

The maximum momentary input energy can be used as an index of intensity of an earthquake, and obtained by Eqn. (5-1). It is considerable that the maximum value of momentary input energy during the total time duration can be obtained by:

$$\Delta E_{\max} = \frac{1}{2} m V_{\Delta E}^{2} \tag{5.1}$$

5. 3 Hysteretic Energy

Input energy in a structural system is balanced (absorbed and dissipated) as follow:

$$E_I = E_D + E_H + E_V \tag{5.2}$$

Where E_I, E_D, E_H, *and* E_V are the input energy, viscous damping energy, hysteretic energy, and kinetic energy. E_H is the portion of the input energy that relates directly to the damage to a structure and therefore it is more meaningful.

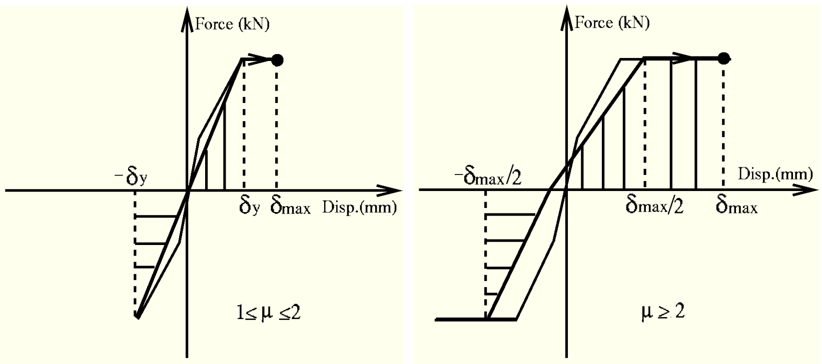

Figure 5.1 analysis model

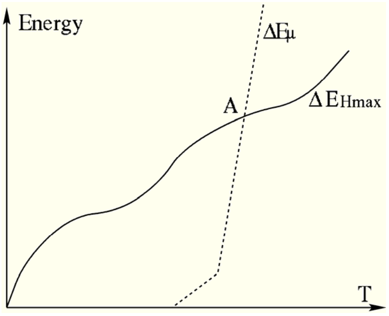

Figure 5.2 crossing point

For an analysis model as shown in the Figure 5.1; damage of structures by energy dissipation evaluated by E_H, is defined by E_μ.

For a given displacement ductility ratio μ, the absorbed energy of structure is related to the amplified ratio of displacement η and maximum ductility μ and expressed as:

$$\Delta E_\mu = f(\mu) F_y \delta_y \tag{5.3}$$

Where:

ΔE_μ : Increment of dissipated energy as shown in Figure 5.2.

F_y : Yielding force δ_y : Yielding displacement

5.4 Dissipated Energy

For a structure, the input energy of earthquake, which is a half cycle of response just before occurrence of maximum displacement is related to the dissipated energy of the structure as:

$$\Delta E_{H\max} = \phi^2 \Delta E_{\max} \tag{5.4}$$

Where ϕ : factor corresponding to the damping ratio and assumed as 0.925.

After plotting $\Delta E_{H\max}$ and $\Delta E_{\max}$ on the same graph, the crossing point is estimating ductility of structure to the earthquake.

The estimating method is summarized as:
1) Calculate $V_{\Delta E}$ from elastic analysis ; 2) Calculate $\Delta E_{\max}$ by using Eqn. 5-1; 3) Calculate ΔE_{μ} corresponding to a given ductility μ by using Eqn. 5-3; 4) Calculate $\Delta E_{H\max}$ by using Eqn. 5-4; 5) Plot $\Delta E_{H\max}$ and ΔE_{μ}, on the same graph, the crossing point (Figure 5.2) is desired ductility

6 RESULT AND DISCUSSION OF RESPONSE

6.1 Energy time history and maximum momentary input energy

Figure 6.1 shows the energy time histories and momentary input energy time histories for CASE-L and CASE-S. It can be seen that for CASE-L there are many instants when the table supplies large amounts of energy to the structure compare with CASE-S, which only one or two large amount of energy were supplied during the whole time duration. The total input energy of CASE-L is larger than CASE-S. However, the maximum momentary input energy is not significantly different. It is considerable that damage of CASE-S was caused by the sudden large input energy in short time, damage of CASE-L was caused by accumulated input energy with effect of repeating input energy in relative long time period.

6-2 Predicted Maximum Response Displacement

Comparisons of estimated maximum response displacements and analyses result obtained by proposed model are listed in Table 6.1 and Figure 6.2. From comparison results it is can be seen that the estimated results have a good agreement with analyzed results.

Table 6.1 Comparisons

Response displacement of Pier (m)	Predicted displacement of Pier (m)
0.054	0.051
0.060	0.064
0.084	0.084
0.132	0.124
0.135	0.150
0.210	0.203
0.215	0.228

7 CONCLUSIONS

The maximum momentary input energy is almost concentrated on initial short time in case of motion with short time duration. It is considerable that for the motion with short time duration sudden inputted large energy in relatively short time period caused account for the significant damage. Damage of motion with long time duration was caused by the accumulated input energy in relatively longer time period. It is possible to predict the maximum dynamic responses by using the concept of maximum momentary input energy. Although it is believed that there still many questions left unanswered, the findings presented in this paper could be used as basic information in improving the seismic performance of reinforce concrete structure.

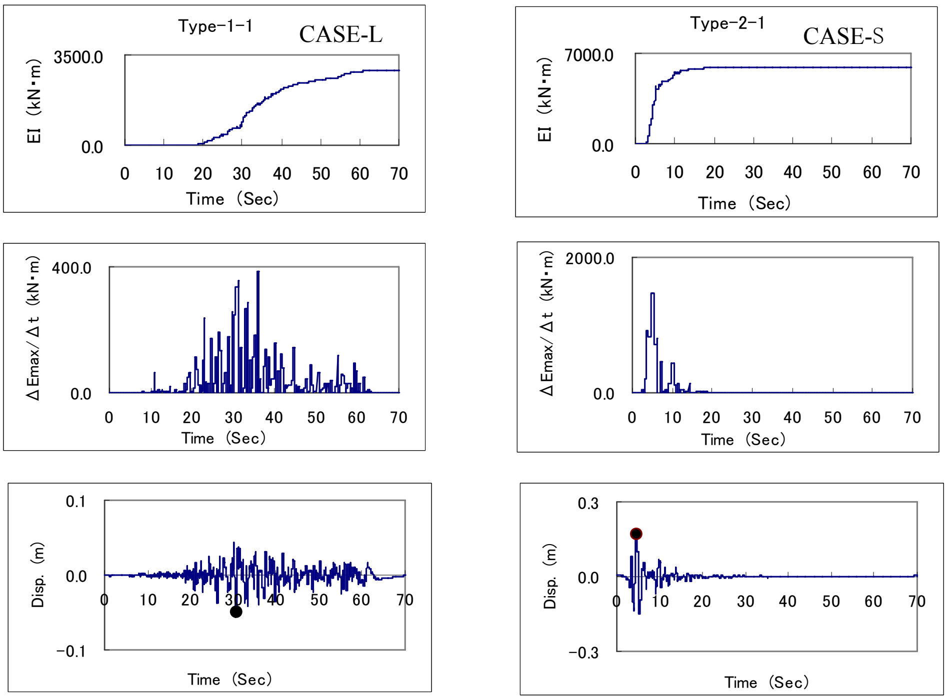

Figure 6.1 Time histories for CASE-L and CASE-S.

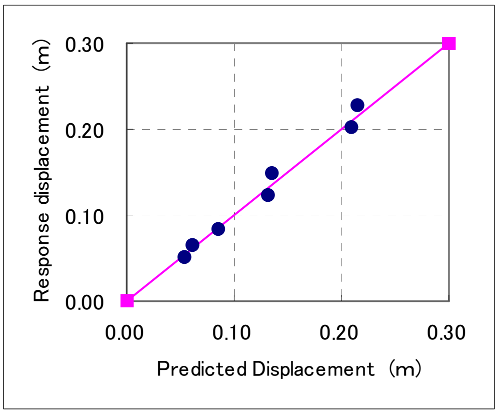

Figure 6.2 Comparisons of estimated displacements

REFERENCES

Wenliuhan.H (1999). The Shaking table tests of reinforced concrete columns subjected to simulated earthquake motions with different time durations, *Journal of Structure Engineering*, **Vol. 45B pp. 313-320**.

Norio.I, Wenliuhan.H (2000). Shaking table tests of reinforced concrete columns subjected to simulated earthquake motions with different time durations, *12WCEE*, **213-222**.

Japan Road Association (2002). Design specifications of highway bridges. Maruzen, Tokyo, Japan