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DAMAGING PROPERTIES OF GROUND MOTIONS AND RESPONSE BEHAVIOR OF STRUCTURES BASED ON MOMENTARY ENERGY RESPONSE

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SUMMARY

Dynamic damaging potential of ground motions must be evaluated by response behavior of structures, and it is necessary to indicate what properties of ground motions are most appropriate for evaluation. For that purpose, behavior of energy input process and hysteretic energy dissipation are investigated in this study.

From motion equation of a single degree of freedom system, total input energy to indicate the cumulative damaging potential and momentary input energy to indicate the intensity of energy input to structures, are applied. By the results of earthquake response analyses, behavior of energy input process is characteristic for each ground motion and it is found that momentary input energy is corresponded to response displacement of structures.

Momentary input energy, that is estimated from pseudo-velocity spectra in either case of elastic and inelastic state, can be used for evaluation of the damaging properties of earthquakes.

INTRODUCTION

Generally, damaging potential of ground motions are measured by its maximum acceleration or velocity. However in recent years, huge acceleration or velocity records are observed for example in Hyogoken-Nanbu (Kobe) and Northridge, and relation between damaging potential of earthquakes and damage of structures is discussed again. Impulsive acceleration of fault earthquake, and cyclic effect of oceanic plate earthquake cause different damages respectively. Therefore these dynamic damaging potential of ground motions must be evaluated by response behavior of structures. It is necessary to indicate what properties of ground motions are most appropriate for evaluation.

In this paper, behavior of energy input process and hysteretic energy dissipation are investigated. Because hysteretic energy of structures are important index corresponding to both of yield force and ductility factor, energy concept is significant to estimate damaging potential of ground motions, and earthquake resistant capacities of structures.

METHOD

Ground Motions:

For input motions, four observed ground motions are used. These ground motions are records of El Centro NS (1940 Imperial Valley), Tohoku University NS (1978 Off Miyagiken), Sylmar County Hospital NS (1994 Northridge) and Japan Meteorological Agency (JMA) at Kobe NS (1995 Hyogoken-Nanbu). Tohoku is record of far source (oceanic plate) earthquake, El Centro, Sylmar and Kobe are near field (fault) earthquakes. Acceleration time histories are shown in **Fig.1**.

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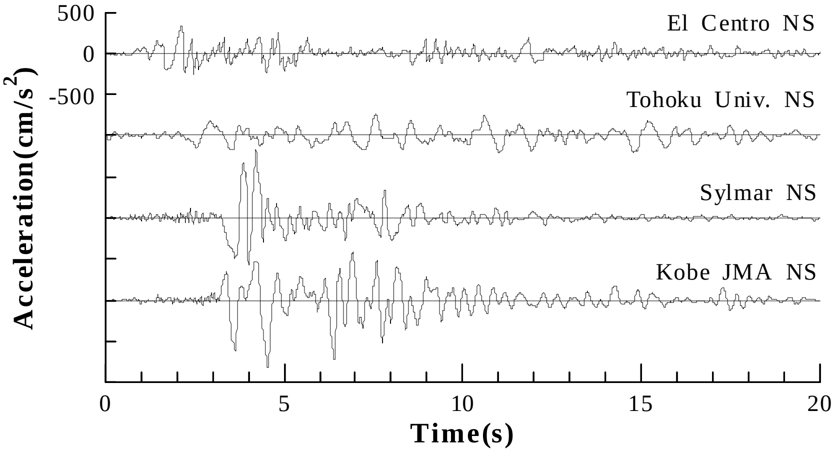


Fig.1 Observed Ground Motions

Energy Response:

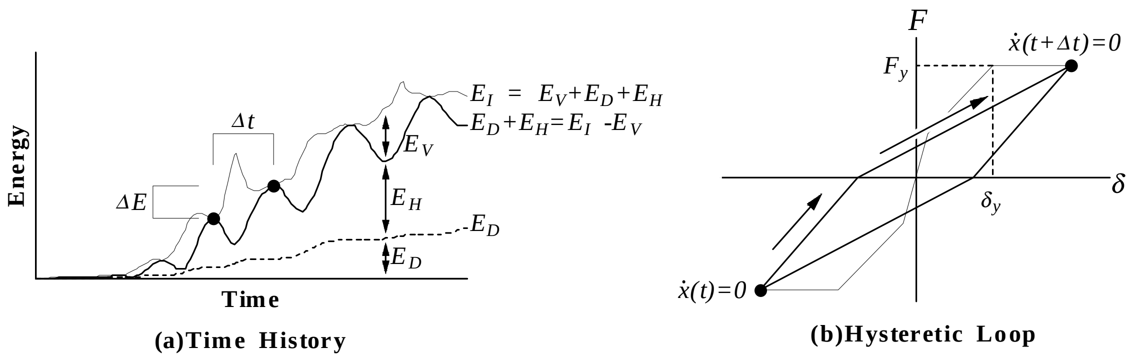
From motion equation of SDOF (single degree of freedom) system, energy equation is given as follows.

$$\begin{array}{ccccccc} \int_0^t D(\dot{x})\dot{x}dt & + & \int_0^t F(x)\dot{x}dt & = & -\int_0^t m\ddot{x}_0\dot{x}dt & - & \int_0^t m\ddot{x}\dot{x}dt \\ E_D & + & E_H & = & E_I & - & E_V \end{array} \tag{1}$$

where m is mass of system, x is displacement, $D(\dot{x})$ is damping force, $F(x)$ is restoring force, $\ddot{x}_0$ is ground acceleration. Input energy E_I is considered to be an index to indicate the cumulative damaging potential of ground motions.

In this study, momentary input energy ΔE is applied 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 ($\dot{x}$ = 0) as shown in **Fig.2**. Δt is a half cycle period of hysteresis loop, and changes for each cycle.

$$\Delta E = \int_t^{t+\Delta t} D(\dot{x})\dot{x}dt + \int_t^{t+\Delta t} F(x)\dot{x}dt = -\int_t^{t+\Delta t} m\ddot{x}_0\dot{x}dt \tag{2}$$



(a)Time History

(b)Hysteretic Loop

Fig.2 Model of Energy Response

DAMAGING PROPERTIES OF GROUND MOTIONS

Time History:

As for elastic SDOF system with natural period T = 0.5sec, mass m = 980ton and damping factor h = 0.05, ground motion levels corresponding to maximum response displacement $\delta_{\max}$ = 5cm are calculated in order to normalize damaging potential. By the results of response analyses, response displacement, input energy E_I and momentary input energy ΔE are shown in **Fig.3**. In this **Fig.3**, momentary input energy is exhibited in terms of ΔE divided by Δt. Area of each rectangle means ΔE and width means Δt. Hatched rectangles are maximum momentary input energy $\Delta E_{\max}$.

It is found that in case of Sylmar and Kobe, input energy is almost concentrated in initial short time range, and total input energy E_I is smaller than Tohoku. Therefore momentary damaging potential of Sylmar and Kobe records to structures are considered to be large. In case of Tohoku, duration time of energy input is long, though maximum momentary input energy $\Delta E_{\max}$ is almost equal to these of Sylmar and Kobe. Therefore, it is considered that structures are damaged by cyclic effect of this ground motion. In all cases ΔE is considered to be related with response displacement, and $\delta_{\max}$ occurs just after $\Delta E_{\max}$ is inputted.

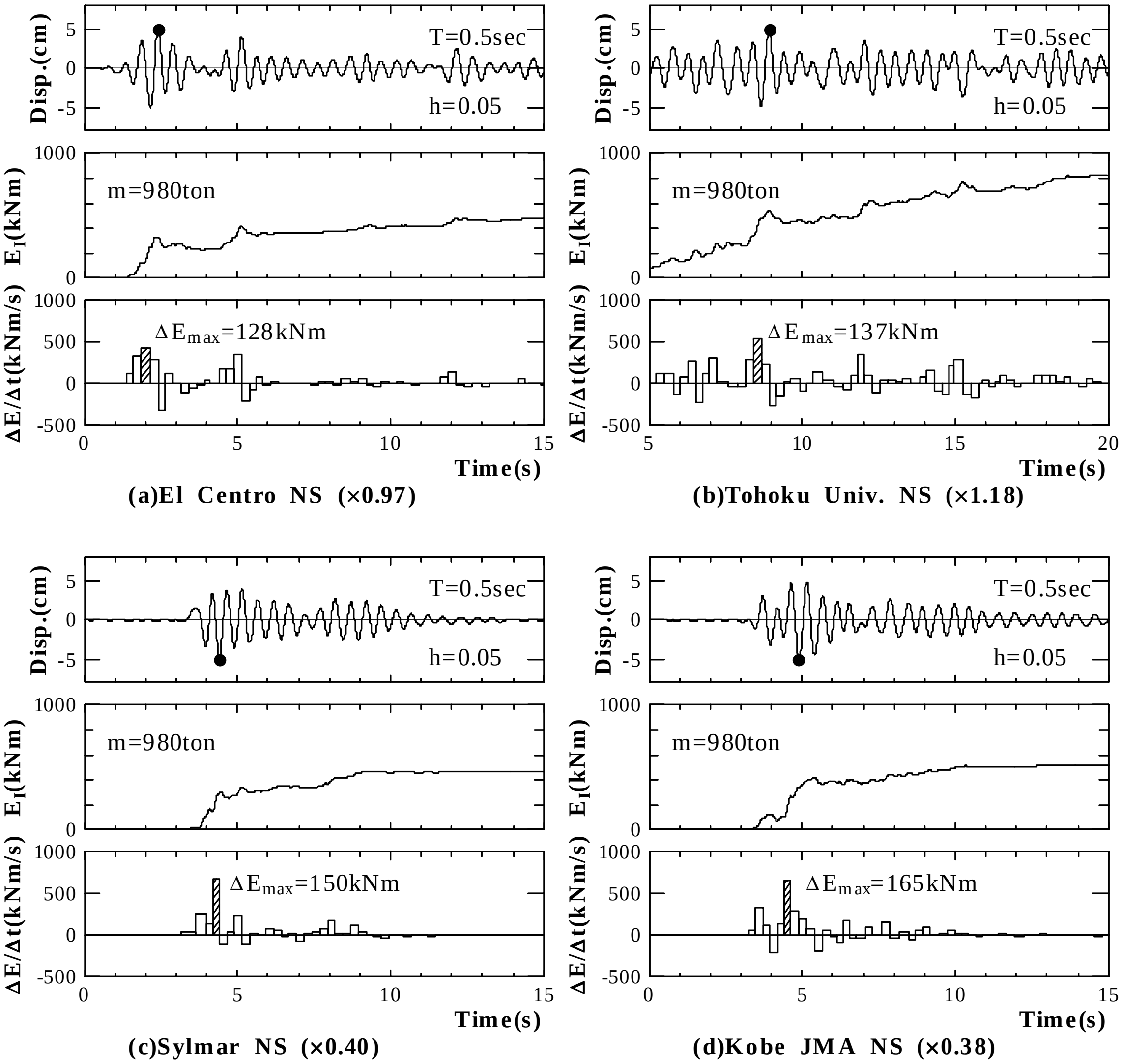
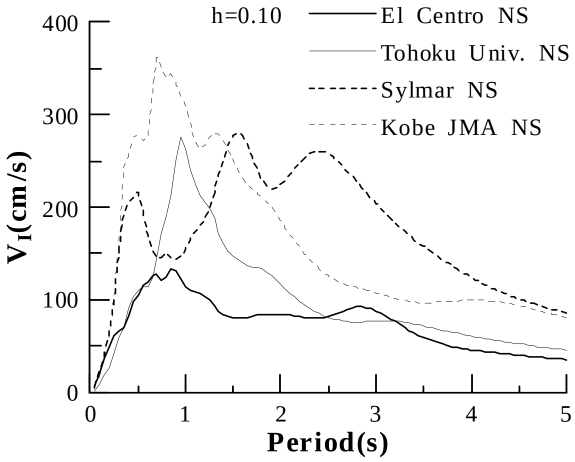


Fig.3 Time History

Spectra:

Total input energy $E_I = \frac{1}{2} m V_I^2$ and maximum momentary input energy $\Delta E_{\max} = \frac{1}{2} m V_{\Delta E}^2$ are shown in **Fig.4** and **Fig.5** respectively, where V_I and $V_{\Delta E}$ are energy equivalent velocity of E_I and $\Delta E_{\max}$.

Total input energy V_I in **Fig.4** is an index to indicate the cumulative damaging potential to structures. Sylmar and Kobe show large values in relatively wide period range, though Tohoku only in near of about 1.0sec. Maximum momentary input energy $V_{\Delta E}$ in **Fig.5** is an index to indicate the intensity of energy input to structures. Because absolute level is large in case of Sylmar and Kobe, both V_I and $V_{\Delta E}$ are large. However $V_{\Delta E}$ in case of Tohoku is smaller than these of Sylmar and Kobe. Therefore ground motion of Tohoku is considered to cause damages to structures by cyclic effects.



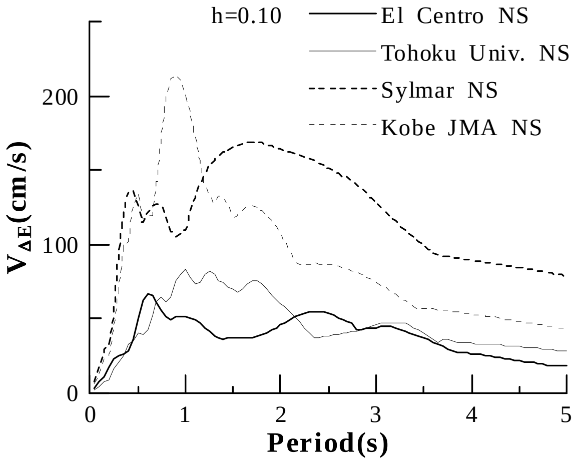


Fig.4 Total Input Energy E_I **Fig.5 Momentary Input Energy ΔE_{max}**

ESTIMATION OF MOMENTARY INPUT ENERGY

Stationary Response:

Stationary response of elastic SDOF system subjected to harmonic force $F\cos(\omega_f t)$, is represented as $x = a\cos(\omega_f t - \theta)$. Dissipated damping energy ΔW during a half cycle (it takes $T_f / 2 = \pi / \omega_f$) is defined as follows.

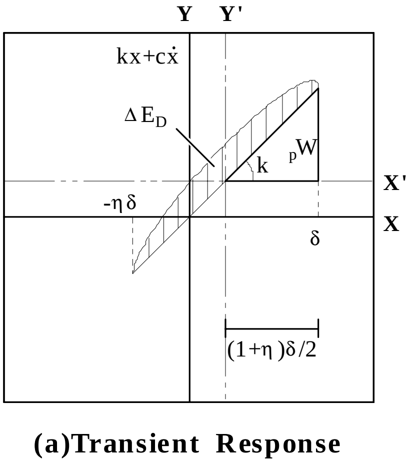
$$\Delta W = \int_{-a}^{a} c\dot{x}dx = \int_{0}^{\frac{\pi}{\omega_f}} c\dot{x}\dot{x}dt = \frac{1}{2}\pi c \omega_f a^2 \tag{3}$$

Energy ratio $\Delta W / W$ during a half cycle is shown as follows where stiffness of SDOF system $k = m\omega_b^2$, natural period $T_b = 2\pi / \omega_b$, damping coefficient $c = 2h\omega_b m$, maximum potential energy $W = \frac{1}{2} k a^2$.

$$\frac{\Delta W}{W} = \frac{\frac{1}{2}\pi c \omega_f a^2}{\frac{1}{2} k a^2} = 2\pi h \frac{\omega_f}{\omega_b} = 2\pi h \frac{T_b}{T_f} \tag{4}$$

Transient Response:

In order to correspond transient response to stationary response, a half cycle of response just before occurrence of maximum response (**Fig.6.a**) is picked up and its equivalent stationary response (**Fig.6.b**) is assumed. Where δ is the maximum response displacement, $\eta\delta$ is opposite displacement before a half cycle of δ, and $\eta\,(0 \le \eta \le 1)$ is amplitude ratio of displacement. η = 0 means pushover type and η = 1 means stationary type response.



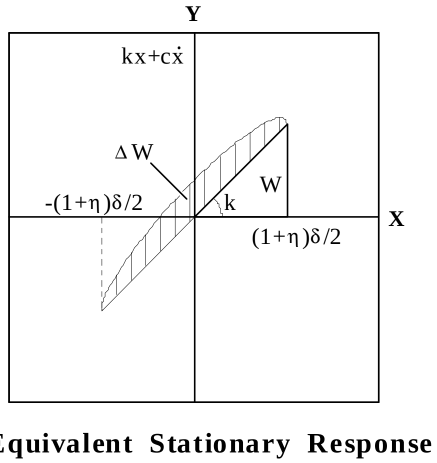


Fig.6 Model of Energy Dissipation

ΔE_D ; Increment of Dissipated Damping Energy on Transient Response

${}_pW$; Pseudo-Potential Energy on Transient Response

ΔW ; Increment of Dissipated Damping Energy on Equivalent Stationary Response

W ; Maximum Potential Energy on Equivalent Stationary Response

$$ {}_pW = W = \frac{1}{2}k\delta^2\left(\frac{1+\eta}{2}\right)^2 \tag{5} $$

By the results of response analyses of SDOF system with various T_b and h subjected to harmonic force (T_f = 1.0sec, $A_{\max}$ = 300cm/s^2), ΔE_D corresponding to $\Delta E_{\max}$, and ΔW given by Eq.(4), (5) are shown in **Fig.7**. Because $\Delta E_D \approx \Delta W$ can be assumed, energy ratio on transient response is given as follows by Eq.(4), (5).

$$ \frac{\Delta E_D}{{}_pW} \approx \frac{\Delta W}{W} = 2\pi h\frac{T_b}{T_f} \tag{6} $$

Earthquake Response:

Energy ratio on earthquake response is shown in **Fig.8** with normalizing by $2\pi h$. Because earthquake motions have predominant period, it is considered that energy ratio increase as natural period of structures become longer, as deduced by Eq.(6). Hence energy ratio on earthquake response is assumed as follows.

$$\frac{\Delta E_D}{{}_pW} = 2\pi h(1.2 + 0.2T_b) \tag{7}$$

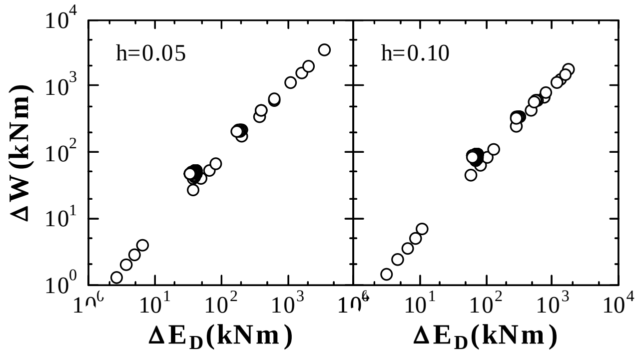


Fig.7 Response ΔE_D and Calculated ΔW

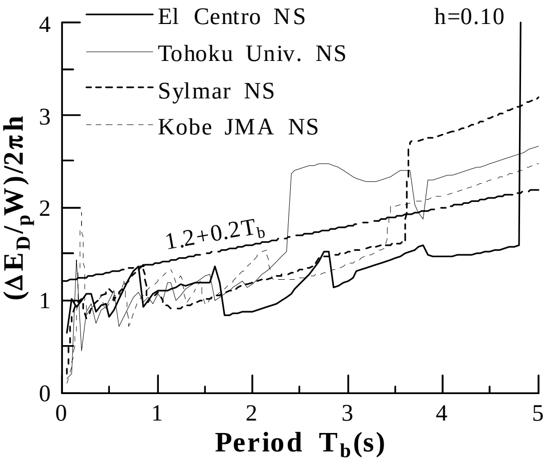


Fig.8 Energy Ratio subjected to Earthquake Motions

Estimation of Elastic $V_{\Delta E}$ Spectra:

ΔE_{max} is given by sum of ΔE_D and ΔE_H, then ΔE_{max} is defined as follows by Eq.(5), (7) and **Fig.6.a**.

$$\Delta E_{max} = \Delta E_D + \Delta E_H = \left\{2\pi h(1.2 + 0.2T_b) \cdot \frac{1}{2}k\delta^2\left(\frac{1+\eta}{2}\right)^2\right\} + \left\{\frac{1}{2}k\delta^2 - \frac{1}{2}k(\eta\delta)^2\right\}$$

$$= \frac{1}{2}k\delta^2\left\{\frac{1}{2}\pi h(1.2 + 0.2T_b)(1+\eta)^2 + (1-\eta^2)\right\} \tag{8}$$

Eq.(8) is rewritten as follows by replacing $\delta = f(h) \cdot \delta_0$ where $f(h)$ is suitable coefficient representing damping effect and δ_0 is maximum displacement in case of h = 0.

$$\frac{\Delta E_{max}}{\frac{1}{2}k\delta_0^2} = \left\{\frac{1}{2}\pi h(1.2 + 0.2T_b)(1+\eta)^2 + (1-\eta^2)\right\} f(h)^2 \tag{9}$$

An example of Eq.(9) for various η and h is shown in **Fig.9**. It is found that ΔE_{max} does not much depend on η and h in case of $h \geq 0.1$. Because this characteristic is observed with another suitable $f(h)$ and T_b, ΔE_{max} can be assumed by a value in case of $h \geq 0.1$ and appropriate η. Eq.(10) is given by substituting η = 1 in Eq.(8).

$$\Delta E_{max} = m\pi h(1.2 + 0.2T_b)(\omega_b\delta)^2 \tag{10}$$

Because Eq.(10) is rewritten as Eq.(11) by energy equivalent velocity $V_{\Delta E}$, $V_{\Delta E}$ can be estimated from pseudo-velocity spectra ${}_pS_V = \omega_b \delta$ with modification by T_b .

$$V_{\Delta E} = \sqrt{\frac{2\Delta E_{\max}}{m}} = \sqrt{2\pi h(1.2 + 0.2T_b)} \cdot {}_pS_V \tag{11}$$

Response $V_{\Delta E}$ (h = 0.10) from elastic response analysis and estimated $V_{\Delta E}$ by Eq.(11) from ${}_pS_V$ (h = 0.10) are shown in **Fig.10**. Almost suitable values can be estimated.

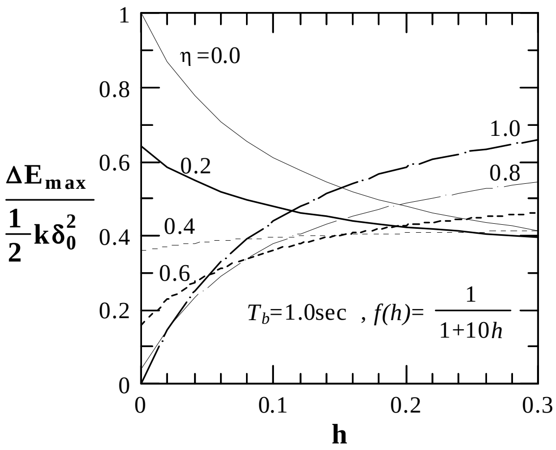


Fig.9 ΔE_{max} given by Eq.(9)

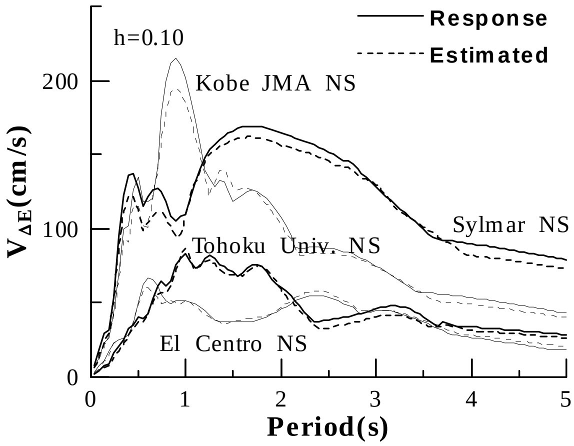


Fig.10 Response and Estimated $V_{\Delta E}$

Estimation of Inelastic $V_{\Delta E}$ Spectra:

In case of inelastic response, period of structures become longer with damage increases. In this study, equivalent period T_e is evaluated by $T_\mu \times 0.75$ as shown in Eq.(12), where T_μ is equivalent period corresponding to secant stiffness of maximum response. 0.75 is a coefficient in order to take transient response into account.

$$T_e = T_\mu \times 0.75 = 2\pi \sqrt{m \frac{\delta_{\max}}{F_{\max}}} \times 0.75 \tag{12}$$

In this paper as for inelastic Force-Displacement relation of SDOF system, Degrading Trilinear type shown in **Fig.11** is used with considering reinforced concrete structures. Viscous damping factor is assumed as h_0 = 0.02 proportional to instantaneous tangential stiffness.

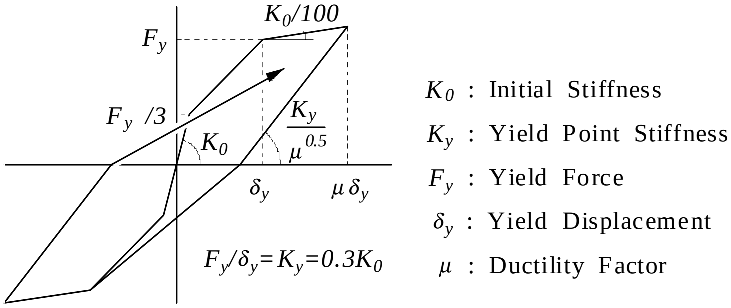


Fig.11 Model for Inelastic Force-Displacement Relation

As for Tohoku and Kobe, elastic $V_{\Delta E}$ (h = 0.1) and inelastic $V_{\Delta E}$ (h_0 = 0.02) with equivalent period is shown in **Fig.12**. Inelastic $V_{\Delta E}$ is nearly equal to elastic $V_{\Delta E}$ and independent of ductility factor μ . Hence it is found that inelastic $V_{\Delta E}$ is estimated from elastic $V_{\Delta E}$, that is, from elastic ${}_pS_V$ or elastic S_D spectra.

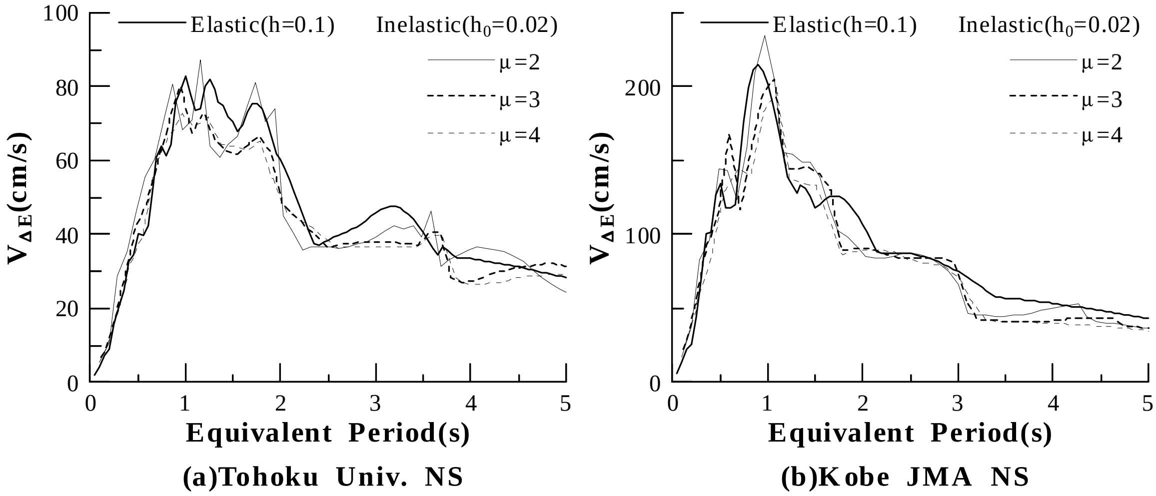


Fig.12 Elastic and Inelastic $V_{\Delta E}$

CONCLUSIONS

In this study energy response of structures subjected to earthquakes is investigated. Momentary input energy is useful to evaluate the damaging properties of earthquakes, and is related to response displacement of structures immediately.

By study of energy ratio in case of stationary, transient and earthquake response, a procedure to estimate momentary input energy from pseudo-velocity spectra, is proposed. And by using equivalent period, inelastic momentary input energy is estimated from elastic one approximately.

As for a structure of which force-displacement relation is known, if quantity of earthquake input energy is given, response level in order to dissipate this input energy, is calculated. Therefore by momentary input energy spectra, maximum inelastic response displacement would be estimated taking damaging properties and type of hysteresis loop into consideration.

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