# EVALUATION OF INPUT ENERGY CAUSED BY EARTHQUAKES AS SEISMIC LOAD FOR HIGHWAY BRIDGES

**Taiji MAZDA[1], Hisanori OTSUKA[2] And Anne S KIREMIDJIAN[3]**

## SUMMARY

Recent heavy damaging earthquakes suggest the importance of considering the elasto-plastic behavior of civil infrastructure systems. Convenient methods for estimating maximum response of bridge structures, like ordinary bridges or seismically isolated bridges, which exhibit elast-plastic behavior under strong earthquakes are proposed in this paper. The total input energy by earthquakes is used as rational seismic load index to evaluate the response. The equilibration of energies between eartquakes and structures is considered in the estimation methods. The estimation methods are applied to single degree of freedom system and multiple degrees of freedom system. To discuss the applicability of the estimation methods, the estimated results are compared with the analitical results using single mass model and FEM model. The estimated results agreed with those obtained by analysis approximately. Applicability of proposed estimation methods based on the equilibration of energies is confirmed.

## INTRODUCTION

Now, civil infrastructure systems are increasingly complex, and the requirements for their performance and safety are also increasingly high. Recent damaging events such as Northridge(1994) and Kobe (1995) suggest the importance of considering the elasto-plastic behavior of civil infrastructure systems, not to mentioning near field ground motion of shallow crustal earthquakes. So, new rational approaches are needed to mitigate the enormous economic losses associate with damage to lifeline and infrastructure system. the revision of current seismic design guideline was conducted immediately after the events. But, it was difficult to do rational revision of the guidelines in limited time considering the relationship with former guidelines. Former guidelines were based on allowable stress design method considering seismic coefficient method in Japan. So, design load index for earthquakes was basically given as a force. These former procedures are simple to design and easy to understand. but, not enough to estimate the nonlinear behavior of bridge structures such as heavy damage events in Northridge and Kobe . So, they are necessary to develop the rational design procedures that can estimate the nonlinear behavior of bridge structures under strong earthquakes without very long computations and to propose the seismic design load index to consider the nonlinear behavior of bridge structures rationally. There were many approaches to evaluate elast-plastic behavior of structure considering energies. [Housner, 1956 & 1959] [Akiyama, 1985] [Kitamura and Akiyama, 1992] [Irie, mazda and Sumaya, 1996 &1997]. The objectives of this research are to develop the rational estimation method which should give accurate response values of bridge structures and to propose the rational seismic design load index considering the equilibration of total input energy and total absorbed energy of bridge structures during strong earthquakes.

[1] *Dept of Civil Engineering, Faculty of Engineering, Kyushu University, JAPAN E-mail:mazda@doc.kyushu-u.ac.jp*
[2] *Dept of Civil Engineering, Faculty of Engineering, Kyushu University JAPAN E-mail:otsuka@doc.kyushu-u.ac.jp*
[3] *Dept of Civil and Environmental Engineering, Stanford University, USA E-mail:ask@ce.stnford.edu*

## INPUT ENERGY BY EARTHQUAKES

**Equation of Energy**

In non-isolated ordinary bridge, a plastic hinge at the base of pier can absorb the input energy caused by the earthquake. The bearings like a lead rubber bearing or high damping rubber bearing are main members that control elast-plastic behavior in seismically isolated bridge. These two types of bridge can be modeled by a single degree of freedom system. The system can evaluate their elast-plastic response during earthquakes. The system subjected to horizontal earthquake can be expressed as following equation.

$$m\ddot{y} + c\dot{y} + f(y) = -m\ddot{z} \tag{1}$$

where
m : mass
c : damping coefficient
f(y) : restoring force
y : displacement of the mass relative to the ground
z : horizontal ground motion

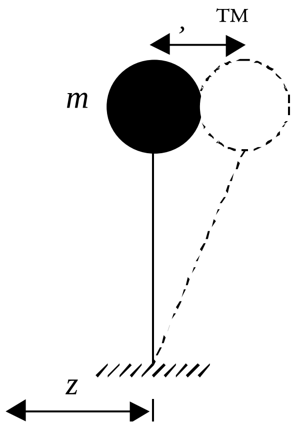



Fig. 1 A single degree of freedom system

The equation of energy is obtained from integration of above equation (1) over the entire duration of the earthquake by $y = \dot{y}dt$ .

$$m\int_0^t \dot{y}\ddot{y}dt + c\int_0^t \dot{y}^2 dt + \int_0^t F(y)\dot{y}dt = -\int_0^t m\ddot{z}\dot{y}dt \tag{2}$$

where
t: duration time of the earthquake

The right-hand side of equation (2) expresses the total input energy caused by the earthquake. The first term of the left-hand side expresses the kinetic energy at the instant when the earthquake motion vanishes. The second term expresses the absorbed energy by equivalent viscous damping. The third term expresses the cumulative plastic strain energy and the elastic strain energy when the earthquake motion vanishes. equation (2) shows fundamental relationship of equilibration of the input energy due to earthquake and absorbed energy of member of bridge.

**Energy Spectrum**

Energy spectrum can be expressed by equivalent velocity $V_E$. $V_E$ is calculated from the assumption that total input energy $E_{total}$ equals with equivalent kinetic energy.

$$V_E = \sqrt{\frac{2E_{total}}{m}} \tag{3}$$

In **Design Specifications of Highway Bridge** in Japan, there are two types of ground motion to be taken into account in seismic design. A plate boundary type large-scale earthquake is assumed as type I. An inland direct strike type earthquake is assumed as type II. The input motion used for time history response analysis is an acceleration wave form obtained adjusting the amplitude of typical past strong motion record based on the frequency zone. Fig. 2 shows type I standard acceleration response spectrum. Fig. 3 shows type II. Each spectrum is classified into three levels depending on ground type. The ground type I is good diluvial ground and rock mass. The ground type III is unstable ground of alluvial ground. The ground type II is not belonging to either ground. Calculated spectra of each type ground motion using equation (2) and equation (3) are shown from Fig. 4 to Fig. 9. Yield load of the system was varied from 0.2 times of total weight W to 0.6 times of W in nonlinear model. Damping constant h is 0.1 in linear model. The equivalent velocity $V_E$ of linear model is larger than $V_E$ in nonlinear model on short period range. So, the nonlinear energy spectrum is more appropriate as a seismic load to evaluate the elast-plastic behavior of member of bridge.

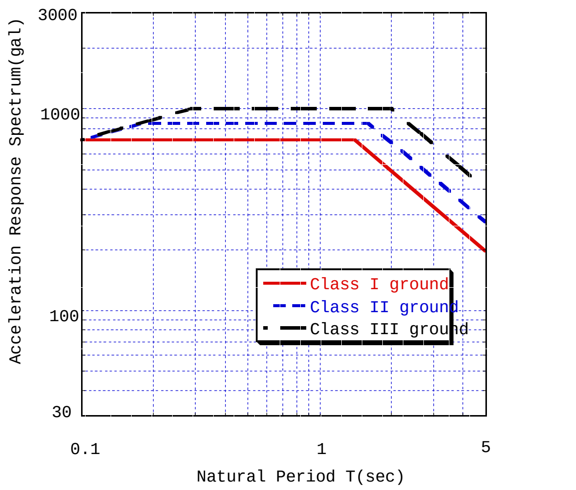



Fig. 2 Type I standard acceleration response spectrum

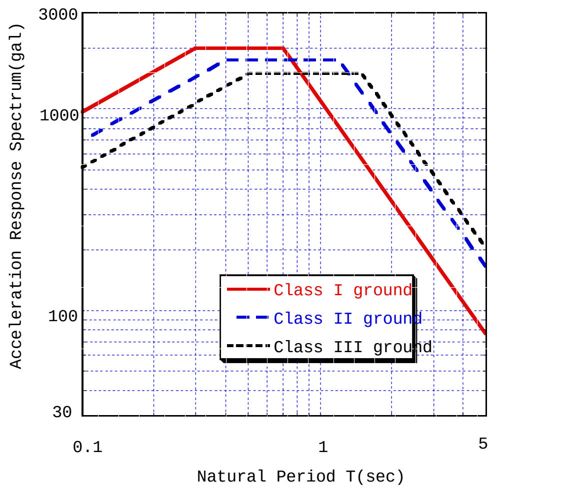



Fig. 3 Type II standard acceleration response spectrum

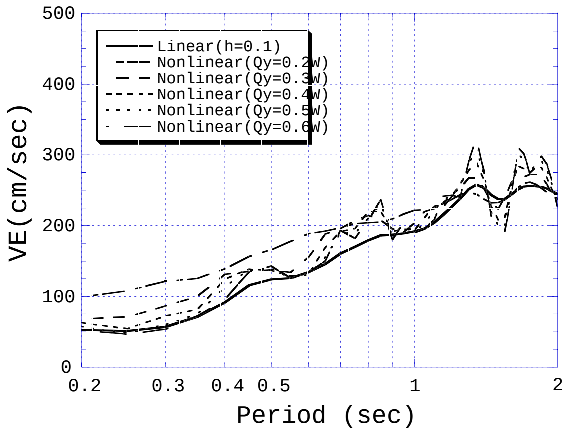



Fig. 4 TYPE I Energy spectrum (Class I ground)

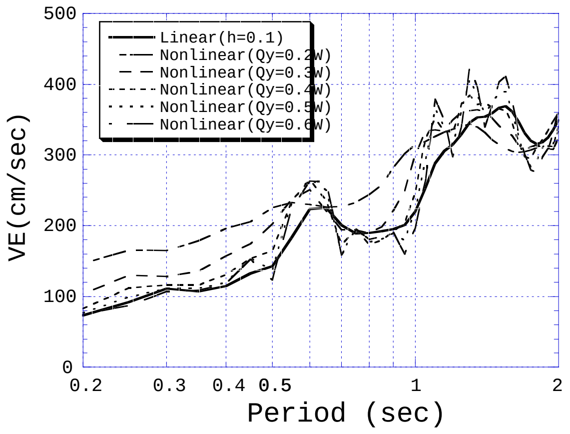



Fig. 5 TYPE I Energy spectrum (Class II ground)

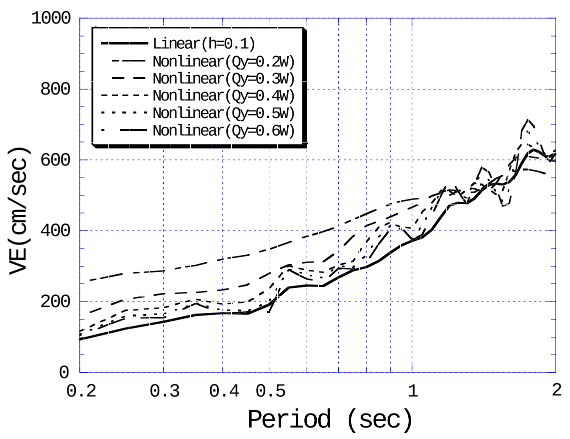



Fig. 6 TYPE I Energy spectrum (Class III ground)

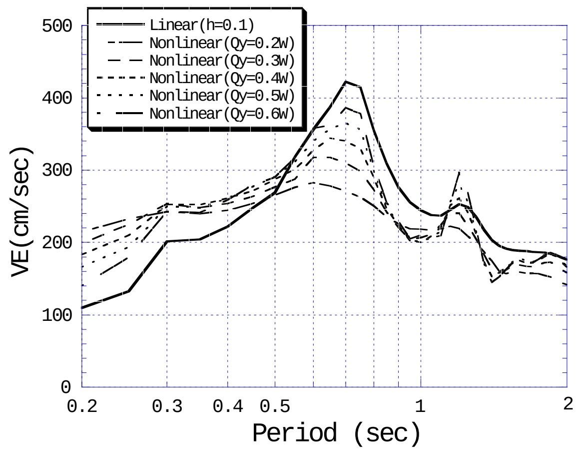



Fig. 7 TYPE II Energy spectrum (Class I ground)

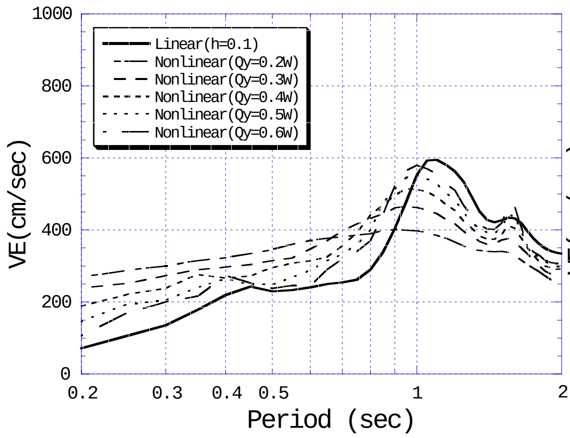



Fig. 8 TYPE II Energy spectrum (Class II ground)

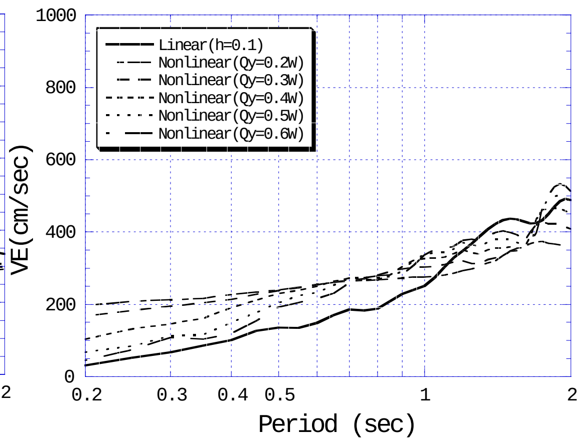



Fig. 9 TYPE II Energy spectrum (Class III ground)

## ENERGY BASED DESIGN OF HIGHWAY BRIDGES

**Single Degree of Freedom System**

The absorbed energy by the pier or the bearing is defined as shown in Fig. 10. Here, the first and second term of the left-hand side of equation (2) are ignored so that the total absorbed energy of bridge can be defined as $\alpha$ times of hysteretic absorbed energy during one cycle $W_{hys}$. $\alpha$ is called herein as hysteretic absorption energy factor. The estimation method proposed is formulated assuming that the total input energy $E_{total}$ given in the right-hand side of equation (2) is equal to the total absorbed energy□ $\alpha W_{hys}$. A principal plastic hinge by bending damage is formed at the base of pier in non-isolated ordinary bridge. On the other hand, a principal deformation occurs at the bearing in seismically isolated bridge. Each bridge can be expressed by using single degree of freedom system.

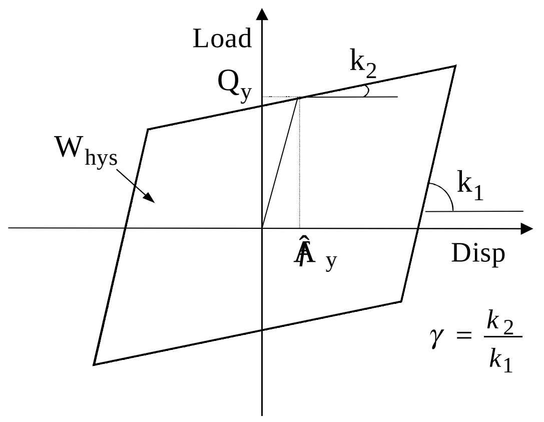
$$E_{total} = \alpha W_{hys} \tag{4}$$

where

$\alpha$ : hysteretic absorption energy factor

$W_{hys}$: hysteretic absorbed energy during one cycle

Fig. 11 shows the flowchart of proposed estimation method. This method uses the equilibration of energies for estimating maximum response. That is, the total input energy due to the earthquake is absorbed by elasto-plastic behavior of member like a pier or a bearing. The ductility factor μ estimated by using this method are checked with the results of time history analysis. The yield load of 0.4W is adopted in the analysis. The comparison of ductility factor between the estimation method using nonlinear energy spectrum and dynamic response analysis in each type ground motion and each ground type are shown from Fig 12 to Fig. 17. In the case of $\alpha$=1 and $\alpha$=2, The estimated results agreed with those obtained by analysis approximately. But the ductility factor of the bridge was underestimated than the analytical results in some period range.




$$k_2 = 0 \quad W_{hys} = 4Qy(\delta_{\max} - \delta_y) \qquad \text{Fpier}$$

$$k_2 \neq 0 \quad W_{hys} = 4(1-\gamma)Qy(\delta_{\max} - \delta_y) \quad \text{Fbearing}$$

Fig. 10 The absorbed energy by the Pier or the bearing

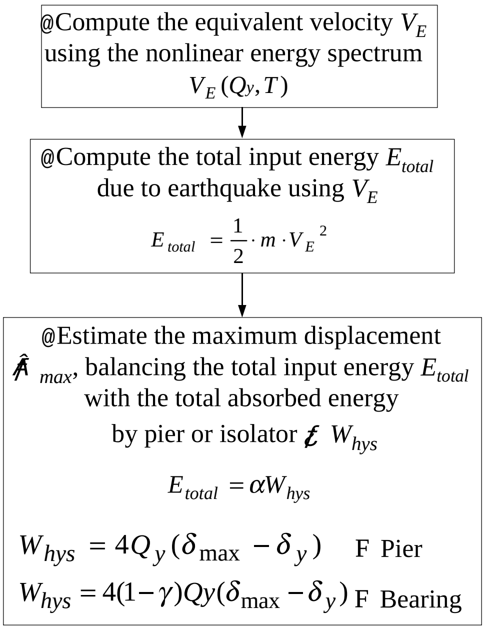



Fig. 11 Estimation method for responses by the equilibration of energies considering pier or isolator

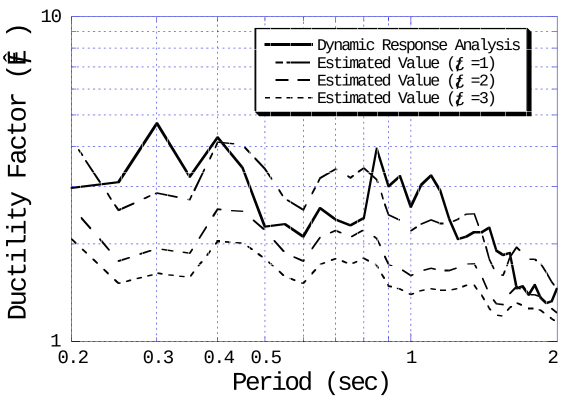



Fig. 12 Comparison of ductility factors between the estimated result and analysis (TYPE I ,Class I ground)

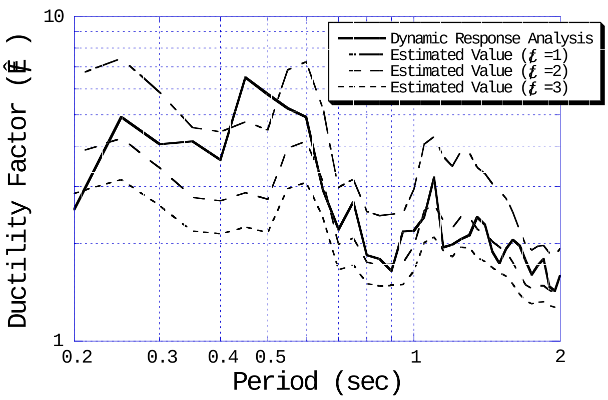



Fig. 13 Comparison of ductility factors between the estimated result and analysis (TYPE I ,Class II ground)

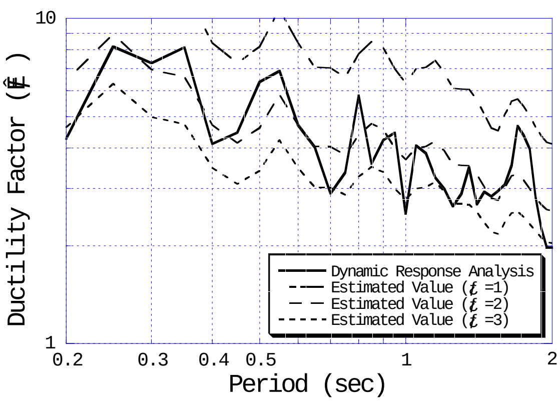



Fig. 14 Comparison of ductility factors between the estimated result and analysis (TYPE I ,Class III ground)

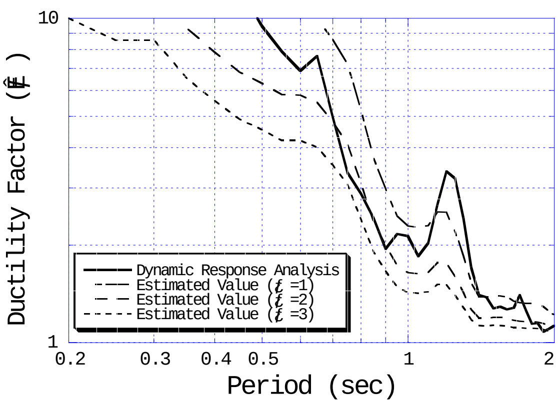



Fig. 15 Comparison of ductility factors between the estimated result and analysis (TYPE II ,Class I ground)

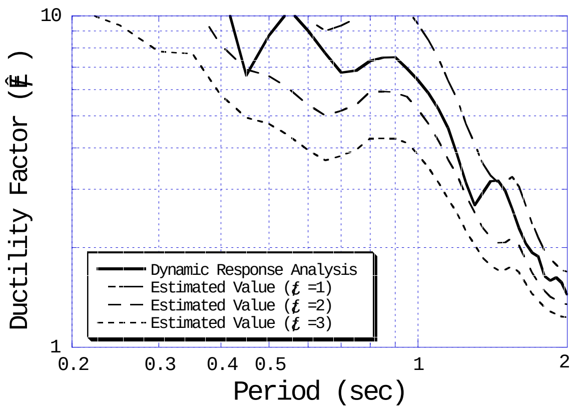



Fig. 16 Comparison of ductility factors between the estimated result and analysis (TYPE II ,Class II ground)

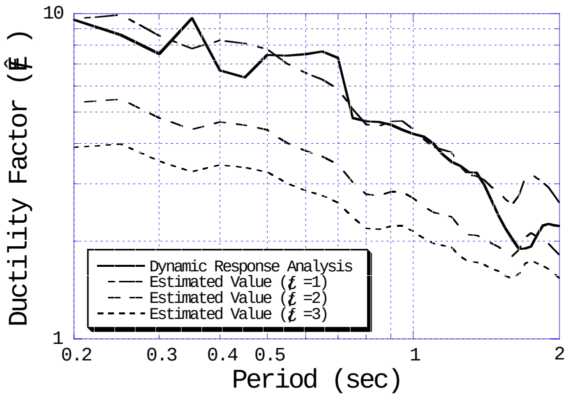



Fig. 17 Comparison of ductility factors between the estimated result and analysis (TYPE II ,Class III ground)

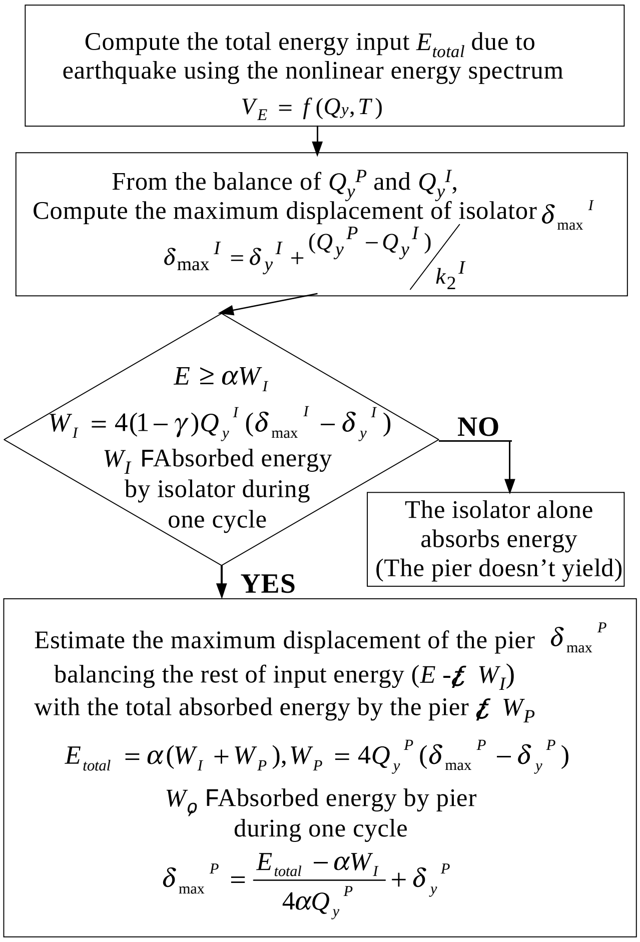



Fig. 18 Estimation method for responses by the equilibration of energies considering pier and isolator

**Multiple Degrees of Freedom System**

In seismically isolated bridge, A plastic hinge at the base of pier and a principal deformation at the bearing occur at the same time when the bridge experience larger earthquake than we expected. This structure can be expressed by multiple degrees of freedom system. In the same manner that the estimation of response in single degree of freedom system is explained by the equilibration of energies, The response of multiple degrees of freedom system may be characterized considering the equilibration of energies. When the earthquake excites the seismically isolated bridge, the response of bridge can be explained based on first mode of the system. If the earthquake is not so large, the bearing will absorb the total input energy. But if the earthquake is larger, the deformation of the bearing increases, and a plastic hinge is made at the base of pier. So it is assumed that the base of pier will be yielded when bending moment caused by shear force of the bearing run up to yield moment $M_y$ of pier. The equilibration between the total input energy and the absorbed energy by members of bridge is shown in equation (5).

$$E_{total} = \alpha(W_I + W_P) \qquad (5)$$

where
$W_I$: hysteretic absorbed energy of the isolator during one cycle
$W_P$: hysteretic absorbed energy of the pier during one cycle

The shear of the energy depends on the ratio of yield seismic coefficient between the bearing and the pier. Fig. 18 shows the flowchart of proposed estimation method. To discuss the applicability of the estimation method, the estimated results were compared with the analytical results using FEM model. An object of the analysis is reinforced concrete single pier on type I ground. Used ground motion is type II earthquake. Table 1 shows the results. The total input energy was evaluated based on the characteristics of the bearing. Natural period of the system to elastic stiffness is 0.98 sec. Yield load of the bearing is 0.1 times of weight of superstructure $W_U$. Equivalent velocity $V_E$ was 210cm/sec. The estimated results were approximately agreed with the analytical results in the case of $\alpha$ =1 and $\alpha$ =2.

Table 1 Comparison of the estimated results and the analytical results

| Yield load (Pier) $Q_y$(tf) | Isolator: maximum disp. $\delta_{\max}^{I}$ (m) | Estimated values | | | Values by dynamic response analysis |
|---|---|---|---|---|---|
| | Pier: ductility factor Ɇ ρ | $\alpha = 1$ | $\alpha = 2$ | $\alpha = 3$ | |
| 0.15$W_T$ | $\delta_{\max}^{I}$ | 0.0766 | 0.0766 | 0.0766 | 0.0775 |
| | Ɇ ρ | 20.5 | 9.67 | 6.04 | 24.7 |
| 0.20$W_T$ | $\delta_{\max}^{I}$ | 0.123 | 0.123 | 0.123 | 0.109 |
| | Ɇ ρ | 11.1 | 4.93 | 2.89 | 15.7 |
| 0.25$W_T$ | $\delta_{\max}^{I}$ | 0.170 | 0.170 | 0.170 | 0.141 |
| | Ɇ ρ | 6.83 | 2.91 | 1.61 | 6.64 |
| 0.30$W_T$ | $\delta_{\max}^{I}$ | 0.216 | 0.216 | 0.217 | 0.183 |
| | Ɇ ρ | 4.63 | 1.91 | 1.00 | 2.48 |
| 0.40$W_T$ | $\delta_{\max}^{I}$ | 0.310 | 0.318 | 0.217 | 0.189 |
| | Ɇ ρ | 2.57 | 1.04 | elastic | elastic |

## CONCLUSIONS

This paper presents two kinds of estimation method considering the equilibration of energies. One is for single degree of freedom system like ordinary bridges or isolated bridges. Another one is for multiple degrees of freedom system like bridges that elast-plastic behavior due to earthquakes occurs in plural members. The following conclusions can be drawn.

1) Total input energy is rational seismic load index to evaluate nonlinear behavior of bridges under strong earthquakes.
2) Proposed estimation method based on the equilibration of energies between the earthquake and the structure can be applied to evaluate the response of the bridges.
3) We need to investigate about rational hysteretic absorption energy factor.

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