APPLICATION OF AN ESTIMATION METHOD FOR RESPONSE OF STRUCTURES BY EQUILIBRIUM OF ENERGIES

Tatsuo IRIE[1], Taiji MAZDA[2] And Allan D SUMAYA[3]

SUMMARY

Seismic isolation bearings effectively reduce inertial forces acting on bridge piers and foundations by absorbing large amount of energies during strong earthquakes. Its nature is determined by its elasto-plastic behavior. Thus, nonlinear responses of seismically isolated bridges depend on the modeling of isolation bearing and method of analysis. The authors proposed a simple method based on the concept of energy equilibrium to provide accurate estimation of maximum responses of seismically isolated bridges or similar structures caused by strong earthquakes. In order to confirm the applicability and accuracy of the method, it is applied in a 292-m-long prestressed concrete box-girder bridge with high damping bearings installed on top of each pier. Each pier is modeled as single-degree-of-freedom (SDOF) system consists of equivalent mass and spring. The spring element is considered to have bilinear type of stress-strain hysteresis defined by elasto-plastic characteristic of isolation bearing and elastic stiffness of pier. Also, time history response analyses of SDOF models as well as frame model of bridge were performed. Comparing the maximum displacements and accelerations of these analyses with the estimations, satisfactory results were obtained. Results reveal that estimations are save values and close with analytic values.

The study results presented in this paper show that the proposed method is convenient and accurate for estimating elasto-plastic maximum responses of seismically isolated bridges under strong earthquakes.

INTRODUCTION

Application of seismic isolation bearings has propagated in structural design of earthquake-resistant structures after learning from the damages caused by major earthquakes in Northridge (1994) and Kobe (1995). In recent years, the use of seismic isolation bearings to design and construction of bridges has become popular in Japan. The bearings distribute and reduce the seismic force acting on piers and foundations; therefore, construction of continuous multi-span bridges becomes possible. Consequently, there would be less expansion joints, which cause noises and vibrations, and vehicle travel would be more comfortable under low maintenance requirements. Moreover, since the Hyougoken-nanbu earthquake, isolation bearings are also applied widely for seismic retrofit of existing bridges. Considering earthquakes having very large magnitude of acceleration and high velocity as observed in Hyougoken-nanbu earthquake, these suggest the importance of rational modelling for elasto-plastic behaviour of bearings, and not to mention the estimation method which should give accurate values without very long computations. There are studies on elasto-plastic response of structures [4, 5], which make use of energy concept in expressing forces and displacements. The authors also presented papers onmethod for estimating maximum responses [2, 3] by balancing the total input energy and the total absorption energy of the bearing.

This paper proposes a simple estimation method based on maximum responses of single-degree-of-freedom systems. It is applied to an actual bridge designed with isolation bearings to confirm its applicability. Maximum responses of single-degree-of-freedom systems varied by different yield loads and restoring force characteristics

[1] CTI Engineering Co., Ltd., Fukuoka, Japan Email: irie@fukuoka.ctie.co.jp
[2] Department of Civil Engineering, Kyushu University, Fukuoka, Japan Email: mazda@doc.kyushu-u.ac.jp
[3] CTI Engineering Co., Ltd., Fukuoka, Japan Email: allan@fukuoka.ctie.co.jp

are computed using energy spectra. In the analysis, two types of ground, namely Type I and Type II, and two seismic load levels, Level II and Level III, are considered. The types of ground correspond to the three types of ground used for seismic design in Japan, generally referred to as Type I, Type II, and Type III [6]. Type I corresponds to base rock ground, Type III to weak ground among alluvial soil layers, and Type II to those of diluvial soil layers or alluvial soil layers which do not belong to Type I nor Type III. Herein, Type III is not considered since it is unsuitable for seismically isolated bridges. The seismic loads are strong earthquakes, which are, for Level II, the standard acceleration waves corresponding to design ultimate horizontal strength method specified in Design Specifications of Highway Bridges-Part V Seismic Design (1996) [6], and for Level III, the acceleration wave recorded during the Hyougoken-nanbu earthquake. Moreover, there are three seismic waves for each level, which are commonly used as standard input seismic acceleration in dynamic analyses.

In order to evaluate the method, estimations are examined and compared to the results of time history response analysis of the actual bridge and single-degree-of-freedom system.

METHOD OF ANALYSIS

In seismically isolated bridges, the bearing (e.g. lead rubber bearing and high damping rubber bearing) is the main element that controls the elasto-plastic behaviour of the system. It can be considered as a single spring having bilinear-type of hysteresis. Similarly, single-degree-of-freedom (referred hereafter as SDOF) systems are modelled to determine its elasto-plastic responses. Estimation of maximum responses by balance of energies using energy spectra is discussed hereafter.

Equilibration of energies:

The key of the estimation method is equilibration of the input energy due to earthquake and absorption energy of bearing. Below shows its fundamental concept.

A SDOF vibration system subjected to horizontal earthquake can be expressed as

$$M\ddot{y} + C\dot{y} + F(y) = -M\ddot{z}_0 \qquad (1)$$

Where M, $C\dot{y}$, $F(y)$, $-M\ddot{z}_0$, $\ddot{z}_0$, and y represent, respectively, the mass of SDOF system, viscous force, restoring force, seismic load, horizontal ground acceleration, and relative displacement of the mass. Multiplying both sides of eq.(1) by $dy = \dot{y}dt$ and integrating the product from t = 0 to t = t_0 gives an equation for equilibration of energies at t = t_0. That is,

$$M\int_0^{t_0} \ddot{y}\dot{y}dt + C\int_0^{t_0} \dot{y}^2 dt + \int_0^{t_0} F(y)\dot{y}dt = -\int_0^{t_0} M\ddot{z}_0\dot{y}dt \qquad (2)$$

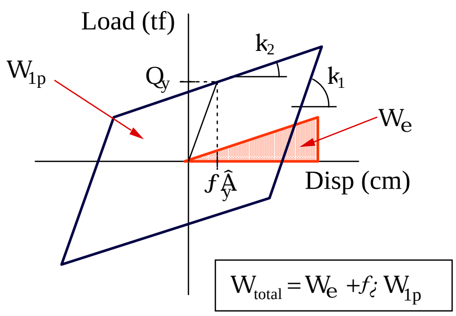


Figure 1: Total absorption energy of structure

In this equation, the right side represents the total energy released by the earthquake to the system; herein, this is called total input energy, $E(t_0)$. On the left, the first term shows the kinetic energy at t = t_0, the second represents the consumed energy due to viscous damping mechanism of the system, and the third corresponds to the elastic strain energy at t = t_0 and absorption energy due to hysteresis of spring [1].

Figure 1 shows the total absorption energy, W_{total}. Here, the first and second term of left side of eq.(2) are ignored so that the total absorption energy of structure, W_{total}, can be defined simply as the sum of elastic strain energy,

W_e, due to post-yield stiffness k_2, and hysteretic absorption energy during one cycle, W_{1p}, multiplied by a certain factor α, called herein as hysteretic absorption energy factor.

Estimation by equilibration of energies:

The estimation method proposed herein is formulated assuming that the total input energy $E(t_0)$, given in eq.(2), is equal to the total absorption energy of structure W_{total}, that is

$$E(t_0) = W_e + \alpha W_{1p} \tag{3}$$

The flowchart in Fig. 2 shows the procedure of the method.

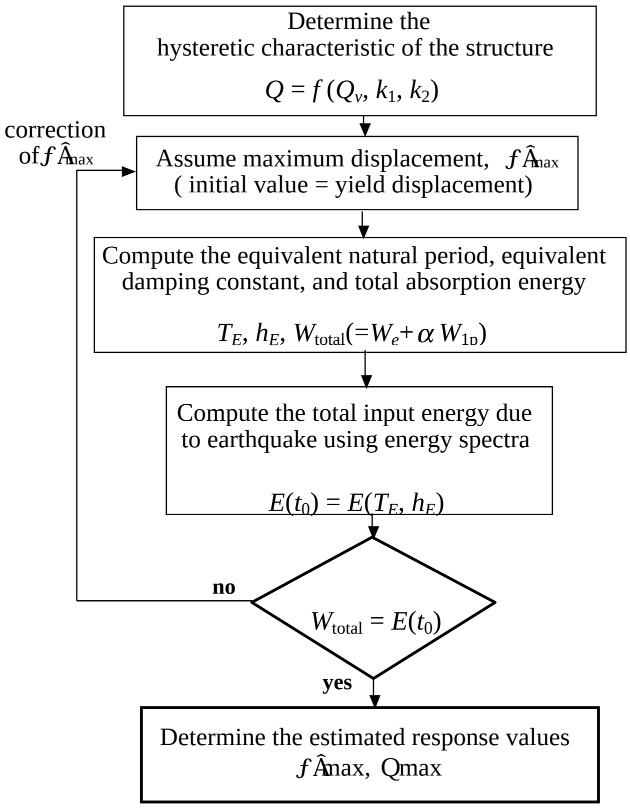
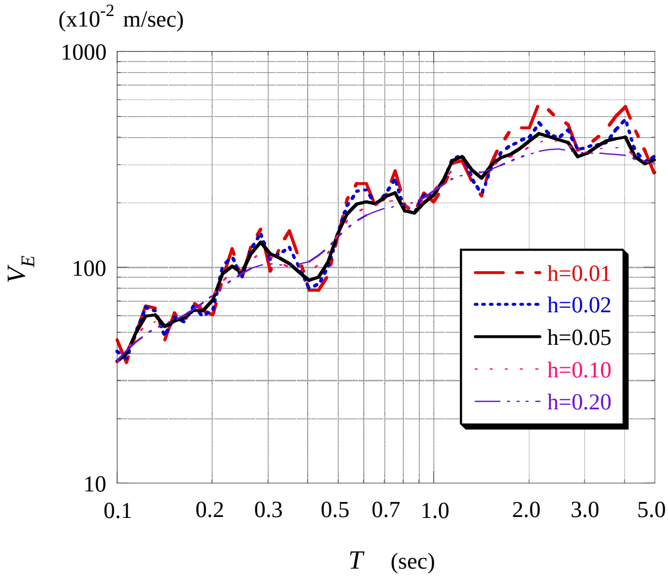


Figure 2: Estimation method for responses by equilibration of energies

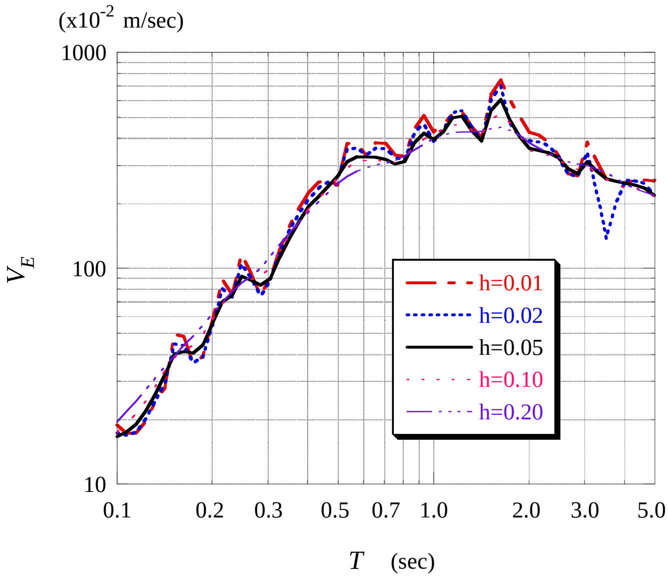
Here, it should be noted that, for convenience sake, the system is considered as an elastic spring in computing for $E(t_0)$. A similar study [7] reveals that maximum responses of elastic system and elasto-plastic system having equal elastic stiffness are almost the same. Figure 3 shows sample energy spectra in Level II and III, for ground Type II, expressed in terms of equivalent velocity given in eq.(4).

$$V_E = \sqrt{\frac{2E(t_0)}{M}} \tag{4}$$

Moreover, since it was found out from previous studies [2, 3] that the hysteretic absorption energy factor α primarily determines the accuracy of the method, α are evaluated with reference to different parameters governing the elasto-plastic characteristics of restoring force.



(a) Level II



(b) Level III

Figure 3: Energy spectra for ground Type II

Hysteretic absorption energy factor:

In Recommendation for the Design of Base Isolated Buildings [5], α is given with a fix value of two. However, the values of α used in this paper are those, which satisfy eq.(3), hence, it depends on the magnitude and characteristics of input wave as well as on the characteristic of restoring force. The average values of α for all cases of hysteresis considered are calculated according to seismic load levels. These values are used to determine the maximum responses of SDOF systems.

There are 96 cases of hysteresis considered, that is, 16 combinations of elastic and post-yield stiffness, and 6 different yield load. Figure 4 shows the parameters used in determining the bilinear hysteretic restoring force of SDOF system, and Table 1 shows the values applied.

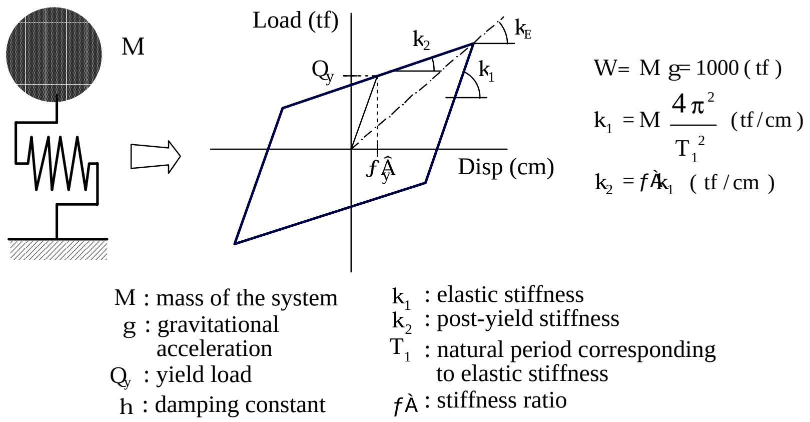


Figure 4: SDOF system with bilinear-type of hysteretic restoring force

Table 1: Parameters of bilinear model

Hysteresis no.	T_1 (sec)	T_2 (sec)	k_1 (kN/m)	k_2 (kN/m)
1-a	0.60	1.04	1119.0	373.0
1-b	0.60	1.20	1119.0	279.8
1-c	0.60	1.47	1119.0	186.5
1-d	0.60	1.70	1119.0	139.9
2-a	0.80	1.39	629.4	209.8
2-b	0.80	1.60	629.4	157.4
2-c	0.80	1.96	629.4	104.9
2-d	0.80	2.26	629.4	78.7
3-a	1.00	1.73	402.8	134.3
3-b	1.00	2.00	402.8	100.7
3-c	1.00	2.45	402.8	67.1
3-d	1.00	2.83	402.8	50.4
4-a	1.20	2.08	279.8	93.3
4-b	1.20	2.40	279.8	69.9
4-c	1.20	2.94	279.8	46.6
4-d	1.20	3.39	279.8	35.0
Q_y = {750, 1000, 1250, 1500, 1750, 2000} (kN)				

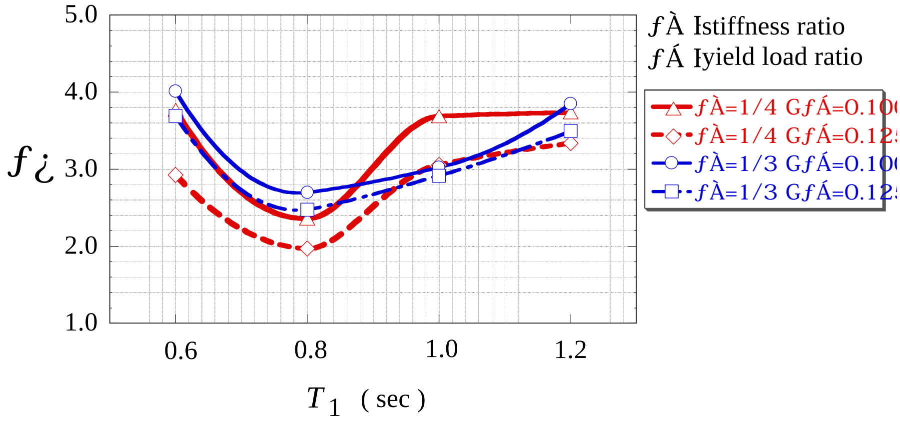
As shown in Fig. 2, method of equivalent linearization is used in balancing energies. The equivalent values for stiffness, damping constant, and natural period can be found using equations (5), (6), and (7), respectively, where W is the elastic strain energy due to equivalent stiffness, and ΔW is the absorption energy during one cycle [6].

$$K_E = \frac{Q(\delta_{\max}) - Q(-\delta_{\max})}{2\delta_{\max}} \tag{5}$$

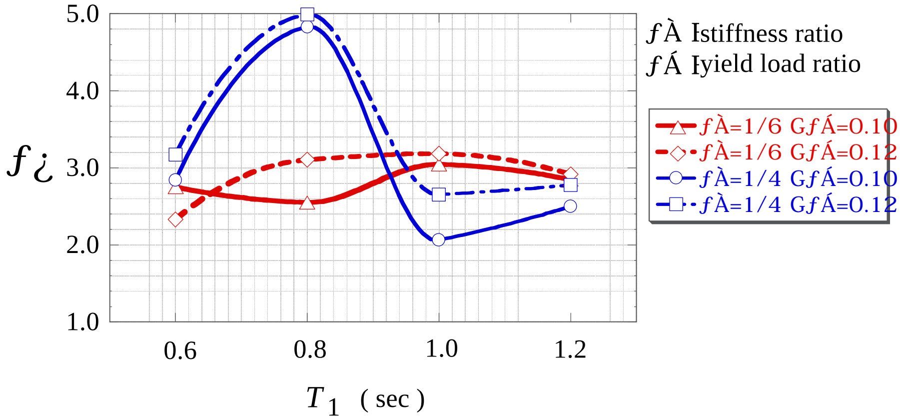
$$h_E = \frac{\Delta W}{4\pi W} \tag{6}$$

$$T_E = 2\pi\sqrt{\frac{M}{K_E}} \tag{7}$$

Figure 5 shows spectra of α for ground Type II, where stiffness ratio and yield load ratio as parameters.



(a) Seismic Level II



(b) Seismic Level III

Figure 5: Values of hysteretic absorption energy factor for ground Type II

Making use of the values of α in Fig.5, maximum responses of structures exhibiting similar elasto-plastic behaviour defined herein can be estimated following the method indicated in Fig. 2.

APPLICATION TO ACTUAL BRIDGE

To sustain the purpose of this study, the above-mentioned method should be objectively examined concerning its level of accuracy and convenience. Thus, applicability of the method is evaluated by considering an actual bridge designed with seismic isolation bearings.

Seismically isolated bridge model:

The bridge used in the analysis is a 292-m-long prestressed concrete bridge with high damping bearings on top of each pier supporting its continuous box-girder (Fig. 6); its ground is of Type II.

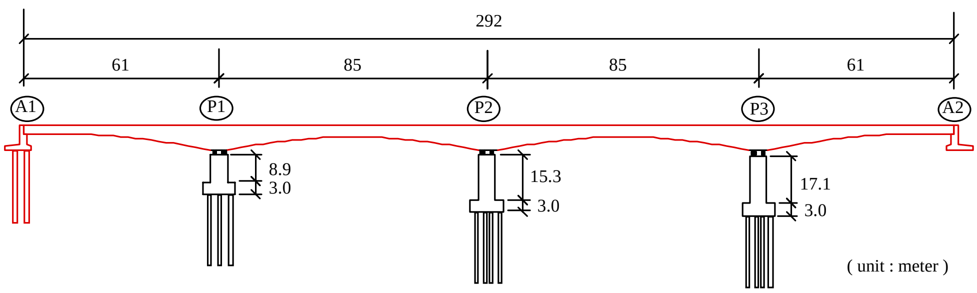


Figure 6: General view of bridge

In the analysis, each pier is modelled as SDOF system consisting of a spring and a mass (Table 2). The spring is defined by non-elastic parameters obtained by combining the elastic spring for substructure (i.e. pier and foundation) and elasto-plastic spring for bearing. The mass corresponds to the weight of the superstructure, which the pier supports.

Table 2: Conditions for analysis

		P1	P2	P3
Weight of superstructure, W	(kN)	25600	25300	25600
Yield load of bearing, Q_y	(kN)	2780 (2610)	2800 (2610)	2810 (2610)
Elastic stiffness of bearing	(kN/m)	153770 (218020)	143120 (218020)	137840 (218020)
Post-yield stiffness of bearing	(kN/m)	26340 (27250)	26180 (27250)	26080 (27250)
Spring constant of substructure	(kN/m)	252200	213200	195000
Elastic stiffness of SDOF, k_1	(kN/m)	95530 (116930)	85630 (107790)	80750 (102930)
Post-yield stiffness of SDOF, k_2	(kN/m)	23850 (24590)	23310 (24590)	23000 (24590)
Stiffness ratio, $\beta = k_2 / k_1$		0.250 (0.210)	0.272 (0.224)	0.285 (0.232)
Yield load ratio, $\gamma = Q_y / W$		0.108 (0.102)	0.111 (0.103)	0.110 (0.102)
Natural period, T_1	(sec)	1.04 (0.94)	1.09 (0.97)	1.13 (1.00)

Note: The values in the parenthesis correspond to seismic Level III.

Comparative results:

The computed values for hysteretic absorption energy factor corresponding to standard input acceleration are shown in Table 3.

Table 3: Hysteretic absorption energy factor

	Level II			Level III		
	1	2	3	1	2	3
P1	4.72	3.52	3.90	2.80	2.81	1.77
P2	4.79	3.42	3.83	2.68	2.51	1.79
P3	4.92	3.50	3.79	2.58	2.32	1.80

The average maximum displacements and acceleration of three standard input accelerations are calculated. These values are shown in Fig. 7, where time history analytic results are compared. Results reveal the following:

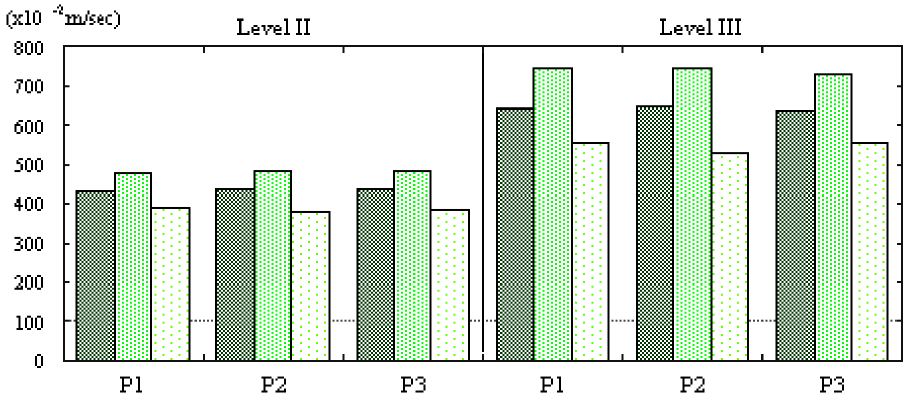
1. Value of hysteretic absorption energy factor differs according to input seismic acceleration. It is found to be approximately 3.8 to 4.9 for Level II and 1.8 to 2.8 for Level III; thus, Level III is smaller than Level to by about 2.
2. Comparing the maximum accelerations and displacements of the two levels, Level III shows larger responses than Level II.
3. The estimation method shows close values with time history response analytic results for frame model of bridge.

CONCLUSIONS

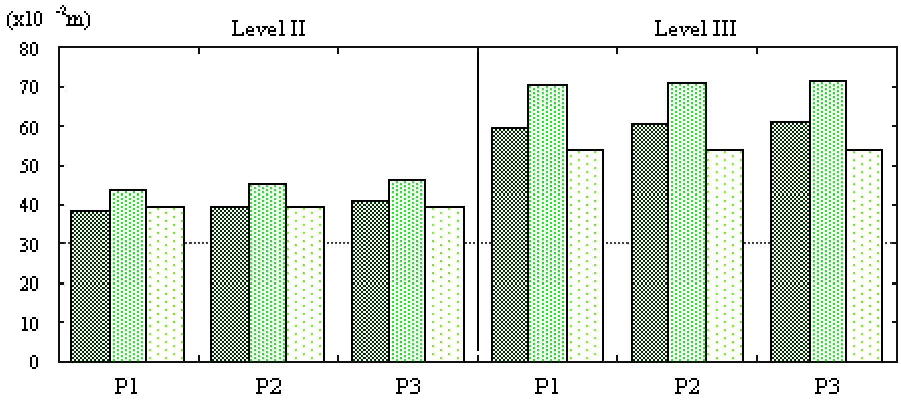
This paper presents an estimation method by equilibration of energies for maximum responses of structures having bilinear-type of restoring force characteristic. After examining the applicability of the method, the following matters were verified.

1. Hysteretic absorption energy factor must be computed according to input seismic acceleration.
2. The estimation method, compared with time history analysis for frame model of bridge, show about an average of 10% and 20% maximum difference in maximum displacement while an average of approximately 15% and maximum of 30% difference in maximum acceleration.

Therefore, the proposed estimation method reveals accurate maximum estimations for convenient seismic design.



(a) Maximum displacements



(b) Maximum accelerations

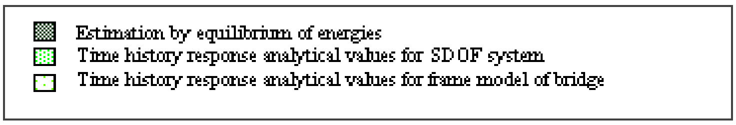


Figure 7: Estimated maximum responses of piers

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