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EVALUATION OF EARTHQUAKE MOTIONS BY ELASTO-PLASTIC RESPONSE OF STRUCTURES CONSIDERING P-DELTA EFFECT

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ABSTRACT

Response spectra are frequently used by engineers and researchers to evaluate the effect of earthquake ground motions to structures. The response spectra, however, are applicable while the response of the structure remains in an elastic range. Since the response exceeds the elastic limit in case of severe earthquakes, the method to evaluate the effect of earthquake motions to structures taking into account the inelastic behavior of the structure are preferable. This is to propose a new method to evaluate the earthquake ground motions considering nonlinear behavior of the structure, *i.e.* yield base shear coefficient spectra.

KEYWORDS

earthquake ground motion; response spectra; elastic base shear; yield base shear;
base shear coefficient spectra; P-delta effect; vertical component

INTRODUCTION

Recently, because of the intense network of strong ground motion observation and the development of strong motion seismometers, it has been obtained that a large number of earthquake records whose maximum acceleration sometimes exceeds $1g$ (where g is the gravitational acceleration). The damage caused by the earthquake, however, does not always coincides with the maximum acceleration or velocity of the ground motion. In order to interpret the ground motion, response spectra are frequently used by engineers and researchers to evaluate the effect of earthquake ground motions to structures. The response spectra give more information than the maximum acceleration or velocity. The response spectra, however, are applicable while the behavior of the structure remains in an elastic range. Since the structural response often exceeds the elastic limit in case of severe earthquakes, the method to evaluate the effect of earthquake motions to structures taking into account the inelastic behavior of the structure are preferable.

Some research has been done previously on inelastic response of systems subjected to earthquake

Newmark (1960) indicated that the response of elasto-plastic systems is closely related to the response of corresponding elastic systems having the same initial slope of the load deformation curve. The maximum accelerations in the elasto-plastic systems, and consequently the design force for such systems, can be obtained as the corresponding quantities for elastic systems multiplied by a reduction factor which depends on the permissible plastic deformation. Riddell (1980, 1995) proposed various forms of inelastic spectra for seismic design, considering the effect of damping, type of material nonlinearity, and the local soil conditions.

The study in this paper is based on the previous studies, although the main objective is aimed at proposing a new method to evaluate the earthquake motions considering the behavior of the structure up to its collapse, *i.e.* yield base shear coefficient spectra, which explain the damage more rationally than elastic response spectra or inelastic design spectra already proposed.

ANALYTICAL MODEL AND PROCEDURE

Considering that the structure can collapse due to P-delta effect even if it has infinite ductility, the analytical model is chosen as follows: It is a single degree of freedom (SDOF) system as shown in Fig. 1 which takes into account P-delta effect. The equation of motion is:

$$\frac{d^2}{dt^2}\phi + 2\xi\frac{2\pi}{T}\frac{t}{dt}\phi + \frac{M(\phi)}{mr^2} = -\frac{\ddot{X}}{r}\cos\phi + \frac{g+\ddot{Y}}{r}\sin\phi \tag{1}$$

where ϕ is the rotation angle, ξ is the fraction of critical damping, T is the natural period, $M(\phi)$ is the restoring moment at the base, r is the height to the mass, $\ddot{X}$ and $\ddot{Y}$ are the horizontal and vertical acceleration of the ground motion, m is the mass and g is the acceleration of gravity. The fraction of critical damping is 0.05 for the elastic analysis and the elastic range of inelastic analysis.

In order to study the effect of earthquake ground motions to collapse structures whose ductility is infinite, the restoring moment for the inelastic analysis is perfect elasto-plastic which means that the ductility of the structure is infinite. But the structure can collapse due to P-delta effect. The yield level is gradually decreased until the model collapses. The collapse is assumed to happen when the rotation angle ϕ reaches $\pi/2$. The maximum yield level that results in the collapse of the structure is the yield base shear coefficient.

Multi-story buildings should have been treated as multi-degree-of-freedom (MDOF) systems. But the collapse mechanism of the most ductile multi-story building is the one that yield hinges are formed at the end of beams. Therefore, the multi-story buildings are treated as SDOF systems as shown in Fig. 2. The period $T(s)$ is taken as $T = 0.1N$ where N is the number of stories and the story height is 4 meters. The story number analyzed is from one to forty ($T = 0.1 \sim 4.0s$).

The input ground motions are El Centro 1940 NS ($0.34g$), Mexico-SCT 1985 EW ($0.17g$), Kushiro 1993 N063E ($0.71g$), Hachinohe 1994 N164E ($0.42g$), and Kobe 1995 NS ($0.82g$). The input ground motions are listed in Table 1. Kushiro record was obtained during the 1993 Kushiro-oki Earthquake through the network of Building Research Institute (BRI) at Japan Meteorological Agency (JMA) Observatory in Kushiro. Hachinohe record was obtained during the 1994 Sanriku-haruka-oki Earthquake at Hachinohe City Hall. Kobe record was obtained during the 1995 Great Hanshin Earthquake at JMA Kobe Marine Observatory. All input ground motions are analyzed with a vertical component simultaneously.

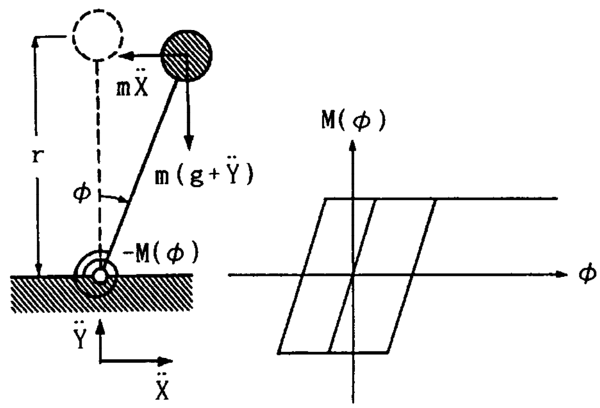

Fig. 1 SDOF analytical model

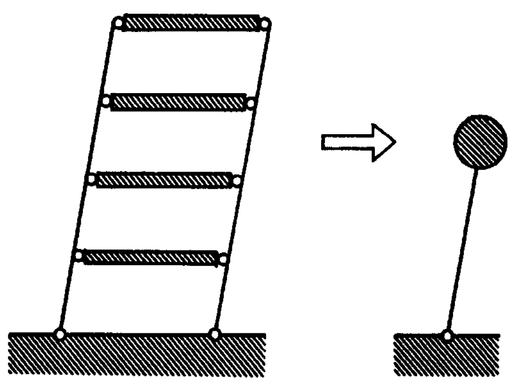

Fig. 2 Equivalent SDOF for MDOF

Table 1 Input ground motions

Earthquake Record	Year	Comp.	Max. Accel. ($gal = cm/s^2$)	Max Vel. ($kine = cm/s$)
El Centro	1940	NS	341.7	33.4
		UD	206.3	8.2
Mexico SCT	1985	EW	167.8	60.5
		UD	36.4	9.0
Kushiro	1993	N063E	711.4	34.2
		UD	363.4	14.8
Hachinohe	1994	N164E	415.9	44.5
		UD	118.7	8.7
Kobe	1995	NS	817.2	90.2
		UD	332.8	39.9

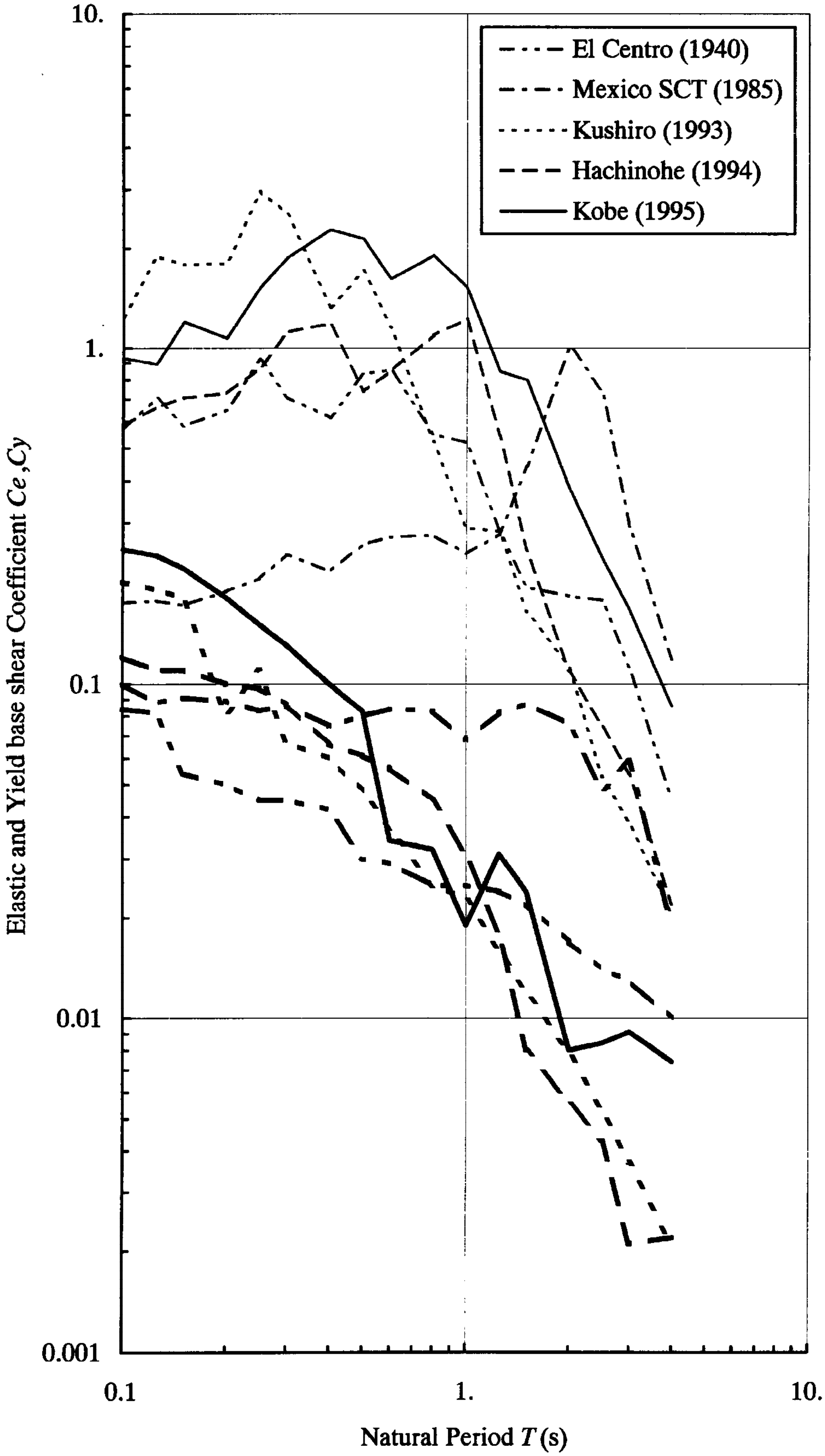

Fig. 3 Elastic and yield base shear coefficient spectra

ANALYTICAL RESULTS AND DISCUSSION

Elastic Base Shear Coefficient

Upper five thin curves of Fig. 3 show the maximum elastic response of the base shear coefficient Ce. Among five earthquake records in Table 1, the elastic base shear coefficient Ce becomes the largest in the shorter period range ($T \leq 0.3s$) of Kushiro record, in the middle period range ($0.3s \leq T \leq 1.7s$) of Kobe, and in the longer period range ($1.7s \leq T$) of Mexico-SCT. This does not explain the damage of the site where each record was obtained.

In the case of the 1993 Kushiro-oki Earthquake, the damage was minor in general and the short period structures ($T \leq 0.3s$) did not suffer any significant damage at the vicinity of the observatory where the record was obtained. In the case of the 1995 Great Hanshin Earthquake, a large number of buildings suffered extremely severe damage regardless of the height and more severe damage concentrated to low and middle rise buildings (AIJ, 1995). The 1985 Mexico Earthquake caused severe structural damage to buildings having six or more stories (UNAM, 1980). Therefore the elastic response spectra do not rationally explain the structural damage.

Yield Base Shear Coefficient

Lower five thick curves in Fig. 3 show the maximum yield base shear coefficient Cy that leads the structure of infinite ductility to collapse. The yield base shear coefficient Cy of Kobe is the largest in the shorter period range ($T \leq 0.5s$). In the longer period range ($T \geq 0.5s$), Cy of Mexico-SCT is the largest. Cy of Kushiro is smaller than that of Kobe in short period range. Therefore, yield base shear coefficient spectra explain the structural damage more rationally than elastic base shear spectra.

CONCLUSIONS

Elastic response base shear coefficient Ce does not coincide with the damage of structures. The yield base shear coefficient Cy shows a good accordance with the damage extent of structures caused by earthquakes. Therefore, Cy v.s. T, which is called as the yield base shear coefficient spectra, can be used to evaluate the effect of earthquake motions to structures.

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