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Empirical formula of equivalent period ratio for isolated structures with viscous dampers

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Isolated structure Viscous damper Response prediction
Equivalent excitation Equivalent period ratio Pulse-like ground motion

1. Introduction

In recent years, there were some studies (e.g. [1-2]) focusing on the energy-based seismic design and response prediction for passive controlled structures with viscous dampers (VDs). However, these studies all used the assumption that the equivalent excitation period of the equivalent simple harmonic load of an earthquake is always equal to the natural period of structure. In reference [3], we had known that for base-isolated structures, this assumption inevitably loses the accuracy guarantee, and the prediction accuracy improvement was investigated when considering the decrease of equivalent period ratio in the energy-based seismic response prediction method proposed by Higashino and Kitamura[1]. However, the ground motion records used in that study are insufficient to propose an empirical formula of the equivalent period ratio for isolated structures. In this paper, a set of 91 pulse-like ground motion records were used to propose an empirical formula for the equivalent period ratio, and a set of 44 far-field ground motion records were used to check the feasibility.

2. Definition of equivalent period ratio

The equivalent period ratio, r_T is derived by regarding a ground motion as an equivalent simple harmonic load, and the definition formula of r_T is [3]

$$r_T = \frac{T_{\mathrm{eq}}}{T_{\mathrm{f}}} = \frac{\omega_{\mathrm{f}}}{\omega_{\mathrm{eq}}} = \frac{2\pi}{T_{\mathrm{f}}}\frac{\delta_{\max}}{v_{\max}} \tag{1}$$

where T_{eq} and ω_{eq} are the equivalent excitation period and equivalent excitation frequency of an earthquake, respectively. T_{f} and ω_{f} are the natural period and frequency of an isolated structure, respectively. $\delta_{\max}$ is the maximum displacement, $v_{\max}$ is the maximum velocity. Thus, the value of r_T can be simply obtained by substituting the time history analysis results of $\delta_{\max}$ and $v_{\max}$ into Eq.(1).

3. Analysis model and ground motion records

SDOF models with long-periods (Fig.1) are established, which represent isolated structures. In Fig.1, M represents the mass, k_{f} is the lateral stiffness of the laminated rubber bearings, c is the damping coefficient of VDs. The period T_{f} used in the analysis is 2.0 s, 3.0 s, 4.0 s, 5.0 s, 60 s and 8.0 s, respectively. The damping ratio of VDs, $\zeta_{\mathrm{d}} = cT_{\mathrm{f}} / \left(4\pi M\right)$ is from 0 to 1.0, interval 0.001.

The presence of velocity pulses in the ground motions generally anticipated in near-fault regions has been known to impose large demands on isolated structures. In this study, the 91 pulse-like ground motion records compiled by Baker[4] were used to propose the empirical formula. All the ground motions were recorded at sites located within 30 km from fault rupture, had a magnitude larger than 5.0, a peak ground acceleration (PGA) larger than 0.1 g, and a peak ground velocity (PGV) larger than 30 mm/s.

This study also used the set of 44 far-field ground motion records utilized in the FEMA P695 project. The ground motions were all recorded at sites located at distance greater than or equal to 10 km from fault rupture, had a magnitude larger than 6.5, a PGA larger than 0.2 g, and a PGV larger than 150 mm/s. Note that there are just nine records out of the 44 far-field ground motions that have pulses in the velocity time history, so this set can represent the situation of ground motions without pulses.

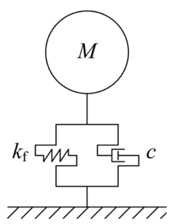
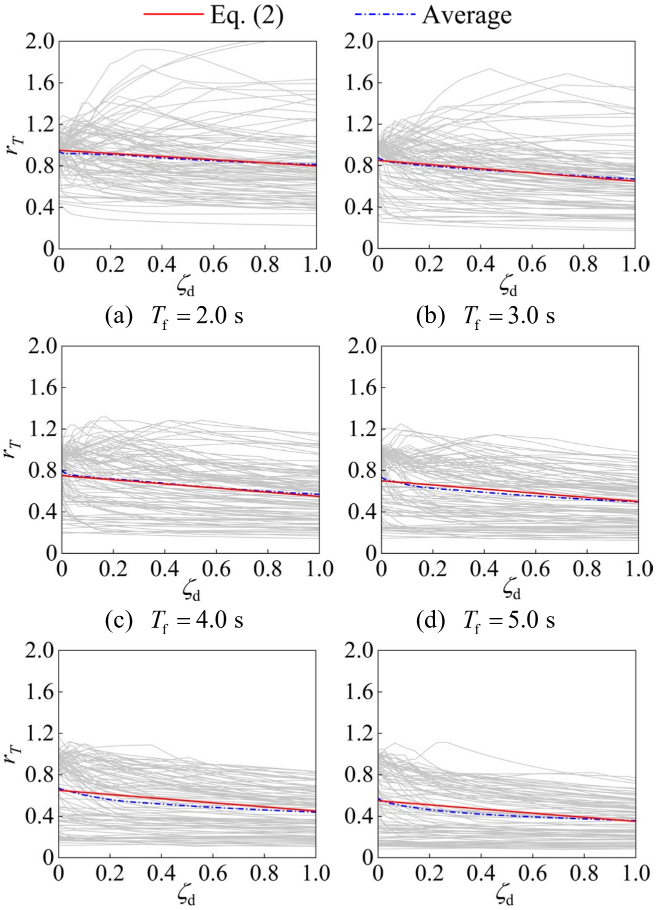


Fig.1 SDOF model

4. Results of 91 pulse-like ground motion records and proposal of empirical formula

By carrying out time history analysis using the model shown in Fig.1 under the 91 pulse-like ground motion records and substituting the analysis results of $\delta_{\max}$ and $v_{\max}$ into Eq.(1), the curves of r_T can be obtained. The results are shown in Fig.2. As can be seen, along with the increase of period and damping, r_T basically has a decreasing trend which is identical with the results shown in reference [3]. Additionally, when the period is under four, there are some extreme results that become larger and deviate from the average curves of r_T. This is because when the period is short, it is easy to be near with the main frequency range of earthquake energy distribution. Along with the increase of period, the extreme situation is improved, and disappear gradually.



(a) $T_f = 2.0$ s (b) $T_f = 3.0$ s
(c) $T_f = 4.0$ s (d) $T_f = 5.0$ s
(e) $T_f = 6.0$ s (f) $T_f = 8.0$ s

Fig.2 r_T under 91 pulse-like ground motion records

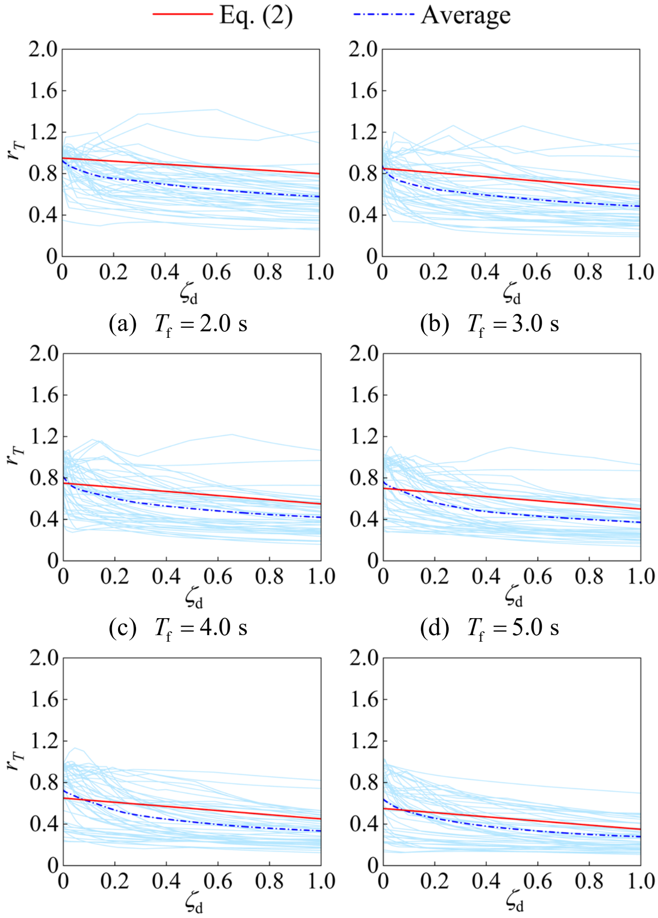
Since pulse-like ground motions are more adverse to isolated structures, this paper proposes the following empirical formula by using the average values of r_T under the 91 pulse-like ground motion records:

$$r_T = \lambda_1 \zeta_d + \lambda_2 \tag{2}$$

where $\lambda_1 = \begin{cases} -0.05T_b - 0.05 & T_b \le 3 \\ -0.2 & T_b > 3 \end{cases}$, is the slope coefficient, $\lambda_2 = \begin{cases} -0.1T_b + 1.15 & T_b \le 4 \\ -0.05T_b + 0.95 & T_b > 4 \end{cases}$, is the intercept coefficient. As can be seen in Fig.2, the curves of the empirical formula Eq.(2) can describe the trends of the average curves well.

5. Results of 44 far-field ground motion records

As same to the obtainment process of r_T under the 91 pulse-like records, the results of r_T under the 44 far-field ground motion records and the curves of the empirical formula Eq.(2) are shown in Fig.3. As can be seen, all the curves of the empirical formula are basically above the average curves, which means the empirical formula is in the safe side for ground motions without pulses. Therefore, it is feasible to use the empirical formula for ground motions without pulses as well.



(a) $T_f = 2.0$ s (b) $T_f = 3.0$ s
(c) $T_f = 4.0$ s (d) $T_f = 5.0$ s
(e) $T_f = 6.0$ s (f) $T_f = 8.0$ s

Fig.3 r_T under 44 far-field ground motion records

6. Summary

This paper investigated the values of the equivalent period ratio for long-period SDOF models which can represent isolated structures. An empirical formula based on the average values of the set of 91 pulse-like ground motion records was proposed, and the feasibility of the empirical formula was checked by the set of 44 far-field ground motion records.

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