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Constant damage inelastic displacement ratios for the near-fault pulse-like ground motions

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ABSTRACT

This manuscript investigates the constant damage inelastic displacement ratios for the near-fault pulse-like ground motions. The inelastic displacement ratios are computed for three hysteretic models and 81 near-fault pulse-like ground motions. The effects of near-fault pulse-like ground motions, period normalization, earthquake magnitude, rupture distance, peak ground velocity (*PGV*), maximum incremental velocity (*MIV*), structural degrading behavior and ultimate ductility factor μ_u are evaluated and discussed statistically. The results indicate that the near-fault pulse-like ground motions can significantly increase the displacement demand of structures with medium period. The period normalization can clearly reduce the dispersion of inelastic displacement ratio. The effect of *MIV* on inelastic displacement ratios is more obvious than *PGV*. The near-fault pulse-like ground motions are more dangerous for structures with strength degrading behavior than ordinary ground motions. A predictive model is proposed for the application of constant damage inelastic displacement ratios for near-fault pulse-like ground motions.

1. Introduction

In the near-fault conditions, due to the effects of forward rupture directivity, most of the seismic energy in ground motion is concentrated in a single pulse of motion at the beginning of the record [1]. These ground motions, referred as “near-fault pulse-like ground motions”, may result in high seismic demands for buildings. Many investigations have studied the effects of the near-fault pulse-like ground motions on the various structures [2–14]. The results in these investigations demonstrated that the near-fault pulse-like ground motions can induce more severe damage of structures than the non-pulse-like ground motions (referred as “ordinary ground motions” here). It is necessary to consider the effects of near-fault pulse-like ground motions in the seismic design and performance evaluation of structures.

In the performance-based seismic design, inelastic displacement ratio is a particularly appealing approach to evaluate the maximum inelastic displacement of structures [15,16]. Many investigations have been conducted to study the characteristics of the inelastic displacement ratios [17–28]. In these investigations, the inelastic displacement ratios are computed for the structures with constant strength [17–24] or constant ductility [25–27]. Recently, the constant damage inelastic displacement ratio is proposed for the seismic design of structures with constant damage performance [28]. The inelastic displacement ratios are calculated for the structures with constant modified Park–Ang damage index value. It is well known that the damage of structure depends both on the inelastic displacement demand and hysteretic energy dissipation [29]. Park–Ang damage index and its modified versions are good measures to quantify the structural damage and have been used extensively in the community of earthquake engineering, because they account for the contribution of inelastic displacement demand and hysteretic energy dissipation to the damage of structure. In comparison with constant ductility inelastic displacement ratio, the constant damage inelastic displacement ratio, which is computed for the structure with constant modified Park–Ang damage index, can contain the more accurate damage of structure in the performance-based seismic design. It should be noted that no near-fault pulse-like ground motion is selected in Ref. [28].

Several studies have investigated the effects of near-fault pulse-like ground motions on the constant strength inelastic displacement ratio or the constant ductility inelastic displacement ratio [30–36]. The results in these studies indicated that near-fault pulse-like ground motions may induce greater inelastic displacement ratios of structures than the ordinary ground motions. However, to the author’s best knowledge, no existing literatures investigated the effects of near-fault pulse-like ground motions on the constant damage inelastic displacement ratio, as defined in Ref. [28]. It is significant to study the constant damage inelastic

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displacement ratios of structures under the near-fault pulse-like ground motions, which is useful for incorporating the effects of near-fault pulse-like ground motion in the application of constant damage inelastic displacement ratios.

This manuscript studies the constant damage inelastic displacement ratios with 81 near-fault pulse-like ground motions and three hysteretic models. The constant damage inelastic displacement ratios are computed with and without period normalization. The influences of near-fault pulse-like ground motions, period normalization, earthquake magnitude, rupture distance, peak ground velocity (*PGV*), maximum incremental velocity (*MIV*), structural degrading behavior and ultimate ductility factor μ_u are evaluated and discussed statistically. The predictive model is proposed for the constant damage inelastic displacement ratios with normalized periods of structures.

2. Inelastic displacement ratios

Inelastic displacement ratio is defined as the ratio of maximum inelastic displacement x_m of an equivalent SDOF model of the structure to the maximum elastic displacement x_e of corresponding elastic structure, having the same period of vibration, when subjected to the same ground motion. Mathematically it can be expressed as:

$$C_{DI} = \frac{x_m}{x_e} \tag{1}$$

where C_{DI} is the constant damage inelastic displacement ratio, x_m is computed for structures whose yield strength varies in order to satisfy the criterion of a constant damage index.

The modified Park–Ang damage index [37] is selected to estimate the damage performance of structures. It is defined as:

$$DI = \frac{x_m - x_y}{x_u - x_y} + \beta\frac{E_H}{x_u F_y} = \frac{\mu_m - 1}{\mu_u - 1} + \beta\frac{E_H}{F_y \mu_u x_y} \tag{2}$$

where x_m is the maximum displacement of structure under ground motion, and μ_m is the corresponding ductility demand; x_u is the ultimate deformation capacity of structure under monotonic loading, μ_u is the corresponding ultimate ductility capacity of structure under monotonic loading; E_H is the hysteretic energy dissipation of structure under ground motion; F_y is the yield strength, and x_y is the yield displacement; β is a positive dimensionless parameter to scale the effect of hysteretic energy dissipation on the final damage of structure. Referring to the investigations [28,38–41], $\beta = 0.15$ is used in this manuscript.

Three different hysteretic models are used in this paper, (i) Elastic-Perfectly-Plastic (EPP) model, representing the non-degrading systems; (ii) Modified Clough (MC) model, simulating the flexural behavior that exhibit stiffness degradation at reloading; and (iii) Stiffness Strength Degradation (SSD) model based on the three parameter model [37,42], representing global behavior of systems exhibiting stiffness degradation and strength deterioration during reloading branches.

In this investigation, constant damage inelastic displacement ratios are computed for inelastic single-degree-of-freedom (SDOF) systems with viscous damping ratio $\zeta = 5\%$. Four damage indices $DI = 0.1$, 0.25, 0.4 and 0.8 are selected to consider the different damage performances. Five ultimate ductility factors $\mu_u = 6$, 8, 10, 12 and 14 are used to include structures with different ultimate ductility capacity. For each ground motion and each damage index, the inelastic displacement ratios are computed for a set of 50 periods or normalized periods between 0.1 and 5.0 with an interval of 0.1. The constant damage inelastic displacement ratio is calculated by gradually reducing the applied strength of SDOF system from the corresponding elastic strength demand until the specified *DI* is achieved within a tolerance (1% is used in this manuscript). The details about the calculation steps of constant damage inelastic displacement ratio can be found in Ref. [28].

3. Ground motions

In Ref. [43], Baker proposed a quantitative classification procedure of pulse-like ground motions, and 91 ground motions with large-velocity pulses in the fault-normal component of records were selected from the approximately 3500 ground motions in the Next Generation Attenuation (NGA) project ground motion library. It is well known that, for the near-fault pulse-like ground motions, the pulse-like signals of fault-normal component are generally more pronounced than fault-parallel component [1,44]. Therefore, 81 fault-normal ground motions are selected from Ref. [43] by excluding the ground motions whose Joyner–Boore rupture distance [45] beyond 30 km. It should be noted that the epicentral distance is used to estimate the Joyner–Boore rupture distance, when the Joyner–Boore rupture distance of a given ground motion is unavailable.

4. Statistical analyses

4.1. Mean inelastic displacement ratios

A total of 81,000 constant damage inelastic displacement ratios C_{DI} of EPP system are computed as part of this investigation, for 81 near-fault pulse-like ground motions, 50 periods of vibration, 4 damage indices, and 5 ultimate ductility factors. Mean C_{DI} are then calculated by averaging results for each period, each damage index *DI*, and each ultimate ductility factor μ_u. It should be noted that, in order to compare with the results in Ref. [28], the periods of structures are not normalized by the pulse period T_p of ground motion or the predominant period T_g of ground motion, and the effects of these parameters will be discussed in Section 4.3.

Fig. 1 shows the mean C_{DI} of EPP system with $\mu_u = 10$. In the short period region (for the period being smaller than 0.5 s in this manuscript), mean C_{DI} change significantly with the variation of the period of vibration and decrease sharply when the period of vibration increases. The well-known equal displacement rule is not applicable in this period region, because the mean C_{DI} are clearly larger than 1.0. In the long period region (for the period being greater than 3.5 s in this manuscript), mean C_{DI} are approximately period independent and vary around 1.0, indicating that the equal displacement rule is reasonable for structures with long periods of vibration, even when these structures are subjected to the near-fault pulse-like ground motions. In the above two period regions, the characteristics of the mean C_{DI} for the near-fault

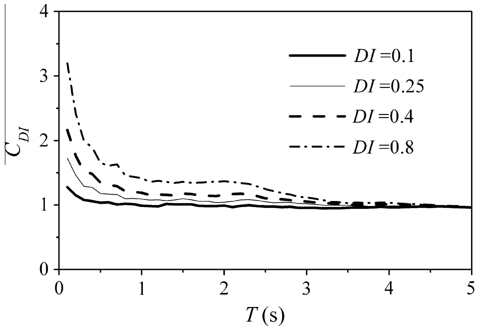

Fig. 1. Mean inelastic displacement ratios C_{DI} of EPP system with $\mu_u = 10$ for 81 near-fault ground motions.