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Residual displacement demands of conventional and dual oscillators subjected to earthquake ground motions characteristic of the soft soils of Mexico City

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ABSTRACT

This paper presents a statistical evaluation of residual displacement (RDs) demands in conventional and dual single-degree-of-freedom (SDOF) oscillators subjected to a set of 220 earthquake ground motions recorded at soft soil sites of Mexico City. A dual SDOF oscillator represents a highly-dissipating energy system (e.g. buckling-restrained braces, BRBs) acting in parallel with a conventional system (e.g. flexible moment-resisting frames). To provide a context, RDs were normalised with respect to the corresponding: a) maximum transient displacements, and b) elastic spectral displacement. The effects of post-yield stiffness ratio (as affected by P-Δ effects), normalised period of vibration with respect to the predominant period of the ground motion, the type of hysteretic response, maximum displacement ductility, lateral strength ratio, type of transition (from elastic-to-plastic response), and damping ratio on normalised RDs were examined for the conventional oscillators. In addition, the effects of the stiffness ratio, lateral strength ratio, displacement ductility, post-yielding stiffness ratio, and type of hysteretic response of the primary and secondary parts of dual SDOF oscillators on normalised RDs were also evaluated. From the results of this investigation, it was observed that for dual SDOF systems the amplitude of normalised RDs is small when the primary part remains elastic. On the contrary, if the primary part exhibits inelastic response, normalised RDs might increase significantly and the post-yielding stiffness ratio of the secondary part plays a key role for constraining them (i.e. while a positive value reduces RDs significantly; a negative value is highly detrimental). Also, it was found that the type of hysteretic response of the primary part of a dual system has a significant effect on normalised RDs (e.g. it was found that a primary part with self-centring capacity, acting in parallel with a highly dissipation system (e.g. BRBs) as secondary part, is very effective for diminishing RDs). A discussion section is also offered to highlight the new findings of this study and differences on normalised RD demands between soft and stiff soils.

1. Introduction

The importance of evaluating residual displacement, or residual drift, demands as a performance parameter to decide whether a building should be repaired or demolished after an earthquake event has been recognised in the up-to-date guidelines for the seismic performance assessment of buildings in the US [1]. Furthermore, Ramirez and Miranda [2] highlighted that economic losses due to earthquakes can be underestimated if the occurrence of excessive post-mainshock residual drifts leading to demolition are neglected in an earthquake loss assessment.

Several studies have focused in assessing the factors affecting the amplitude of residual displacements (RDs) of conventional single-degree-of-freedom (SDOF) oscillators (e.g. [3–6]), and some of them also proposed empirical expressions to estimate RDs for simple structures that can be represented as SDOF systems. For instance, MacRae and Kawashima [3] conducted a parametric study in 2%-damped SDOF bilinear oscillators subjected to 11 ground motions recorded in stiff, medium, and soft soils. The authors found that RDs are highly dependent on the post-yielding stiffness ratio, r (i.e. a negative r produced very high RDs while a positive r produced small RDs). They also reported that the type of ground motion, period of vibration, and peak target ductility did not have a significant effect on RDs. From their results, they proposed a method to estimate RDs for

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simple structures with different values of r, a damping ratio of 2%, and a target ductility demand, μ, equal to 4. Years later, Christopoulos et al. [4] conducted a study to evaluate RDs, measured as the ratio of residual-to-maximum displacement demands, of four equivalent 5%-damped SDOF oscillators representative of four reinforced concrete buildings subjected to 20 spectrum-matched earthquake ground motions. Three hysteretic models were used in their study namely: 1) elastoplastic, representative of steel framed structures, 2) Takeda [7], representative of reinforced concrete framed structures, and 3) Flag-Shape [8,9], representative of structures with self-centring capacity. Also, post-yielding stiffness ratios between −0.10 and 0.10 were evaluated. The authors found that the type of hysteretic model, post-yielding stiffness ratio, and seismic intensity affect both RDs and their dispersions significantly. Particularly, they concluded that structures with self-centring capacity significantly constrained RDs with respect to structures having elastoplastic and Takeda-type global hysteretic behaviours, while similar displacement ductility demands were observed in the three hysteretic models. After that, Ruiz-García and Miranda [5,10] proposed an equation to estimate a dimensionless parameter called residual displacement ratio, C_r, which allows the direct estimation of RDs of elastoplastic SDOF oscillators from elastic spectral displacement ordinates. The fitted parameters for the introduced equation were obtained from regression analysis using the statistical response of 5%-damped elastoplastic SDOF oscillators subjected to 240 ground motions recorded in firm sites of California, USA. According with the equation proposed by these authors, C_r was a function of the period of vibration (T), the lateral strength ratio (R_y), and the type of soil. A similar study was carried out by Ruiz-García and Miranda [10] to compute C_r ratios from the response of elastoplastic and stiffness-degrading SDOF systems subjected to 40 near-fault earthquake ground motions having forward-directivity effects. They concluded that the spectral shape of C_r is influenced by the pulse period, T_p, identified in the ground velocity waveform, the peak ground velocity, and the level of unloading stiffness in the stiffness-degrading hysteretic models. Very recently, Liossatou and Fardis [6,11] conducted an extensive statistical study on residual displacements, described by C_r and residual/maximum ratios, of SDOF systems using three types of hysteretic models representative of reinforced concrete (RC) structures, namely: good quality, fair quality, and poor quality RC construction. The results were compared to the results from bilinear models without stiffness and strength degradation. The most significant conclusion of the study was that RC oscillators present smaller C_r and residual/maximum ratios than the bilinear oscillators. The RDs were from larger to smaller in the following order: bilinear, RC of good quality, RC of fair quality and RC of poor quality. They also reported that velocity pulses of the ground motions increase both, residual and peak inelastic displacements in similar proportion, and they confirmed that the amplitude of C_r ratios depends on T_p. As an alternative approach for post-seismic evaluation, Hatzigeorgiou et al. [12] and Christidis et al. [13] introduced simple empirical equations to estimate maximum displacements from residual displacement demands to be applicable to simple structures and steel frames, respectively. Recently, a review of existing methods for evaluating residual drift demands in steel framed buildings is reported in Ref. [14].

After searching the literature, it has been observed that RDs are dependent on the post-yielding stiffness ratio, the period of vibration, the lateral strength ratio, the level of ductility demand, the type of soil, and the type of hysteretic behaviour [3–5,10,11]. However, there is still very limited information about the effects of the aforementioned parameters on RDs triggered in structural systems subjected to earthquake ground motions recorded in very soft soil sites (i.e. narrow-band motions characterised by long predominant periods, low frequency content, and long duration) such as those found in Mexico City, and only the work of Bojórquez and Ruiz-García [15] examined residual drifts demands. In their study, the authors developed peak and residual inter-story drift demand hazard curves for four typical steel moment-resisting frames designed according to the 2004 Mexico City Building Code [16] when subjected to 30 records gathered in accelerographic stations located in the lake-bed zone of Mexico City. They found that the amplitude of residual drift demands strongly depended on the members' post-yield stiffness ratio (e.g. increasing post-yield stiffness ratio from 1% to 3% decreased residual drift demands as the seismic intensity increased). They also reported that if the case-study frames would experience maximum inter-storey drifts around 3%, they also could exhibit residual inter-story drifts of approximately 1%, which may lead them to demolition.

Dual structural systems consisting of highly-dissipating energy systems (e.g. buckling-restrained braced frames) acting in parallel with a conventional system (e.g. flexible moment-resisting frames) such as those proposed in Refs. [17–19] are very attractive in highly active earthquake-prone regions such as Mexico City. However, they might be subjected to large residual displacement demands due to the wide hysteretic features of the energy-dissipating elements [20,21]. As an example, Kiggins and Uang [21] concluded that BRBFs acting as lateral-load resisting system might experience large residual displacement demands, and that they should incorporate moment-resisting frames acting as a restoring system to be designed as a dual system. This observation was confirmed in subsequent studies carried out by Pettinga et al. [22], Terán-Gilmore et al. [23], as well as Sahoo and Chao [24]. Therefore, the amplitude of residual displacement demands of such dual structural systems in buildings built on soft soil conditions should be investigated before their practical implementation.

The objective of this paper is to present main results of a statistical study focused on evaluating residual displacement demands, in terms of the residual-to-maximum displacement ratios and C_r ratios, for simple structures representative of conventional and dual structural systems, subjected to a relatively large set of 220 accelerograms recorded in Mexico City. Since practical applications may require residual displacement demands in absolute terms, they can easily be obtained by multiplying the results presented in this paper by the corresponding maximum displacement demands (which may be calculated from [25]) or the elastic spectral displacement ordinates (which are commonly available to designers), as appropriate. It is worth to highlight that, in this study, the response of conventional systems refers to the response of SDOF oscillators, while the response of dual systems is related to the response of coupled primary and secondary SDOF systems acting in parallel. The latter systems are aimed at representing highly-dissipating energy systems (e.g. buckling-restrained braced frames) acting in parallel with a conventional system (e.g. flexible moment-resisting frames) such as those proposed in Ref. [23]. In this paper and to be consistent with [26], the primary part of the dual system refers to the main structural system (e.g. moment-resisting frames) while the secondary part refers to the energy dissipation system.

Although this work introduces new findings on the subject, it is constrained to the response of SDOF oscillators. However, it should be recognised that residual displacements and residual inter-storey drifts in multiple-degree-of freedom systems (e.g. multi-storey buildings) depend on additional variables such as higher-mode effects, P-Δ effects, type of sway mechanism, and type of member hysteresis characteristics (e.g. [27,28]) that are not accounted for in SDOF oscillators. These effects can be approximately taken into account by scaling the RDs of SDOF oscillators (e.g. those presented in this study) using amplification factors, such as those discussed in Refs. [27,28] for moment-resisting frames. A study to estimate amplification factors in multi-storey structures equipped with BRBs is the subject of a further study and the results will be available in the future. Another consideration, that the reader must be aware of, is that soil-structure interaction (SSI) effects have been neglected in this study and the results presented should be interpreted in that light. Certainly, stiff structures located in soft soils tend to be affected by these effects. The issue will be addressed in a future paper.