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On the use of the equivalent linearization for bilinear oscillators under pulse-like ground motion

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A B S T R A C T

The equivalent linearization is a well-known simplified approach for estimating the maximum absolute displacement of inelastic systems, being widely adopted in many technical codes and guidelines. In this regard, the present paper addresses the use of the equivalent linearization to estimate the peak displacement of bilinear oscillators with known displacement ductility subjected to near-fault pulse-like earthquakes. An extensive numerical investigation is initially performed in order to evaluate the accuracy of a recent equivalent viscous damping formulation. The analysis of the obtained numerical results reveals how the predictive capability of the equivalent linear model depends on the ratio between elastic period and pulse period of the ground motion. A corrective factor is then proposed in such a way to improve the prediction of the peak inelastic displacement in case of pulse-like seismic waveforms. Numerical results demonstrate that the proposed correction leads to more robust and accurate estimates, especially for low hardening ratio values and mid-large pulse periods.

1. Introduction

Simplified approaches for estimating the peak displacement of inelastic single-degree-of-freedom (SDOF) systems are adopted in many technical codes and guidelines for the seismic assessment and design of structures. The most common ones are based on the displacement modification factor or the equivalent linearization. The displacement modification factor, for instance, was adopted by ASCE-FEMA [1] and it can be formally defined as the ratio between the ordinate of the inelastic displacement spectrum for a given period and the corresponding elastic value. The methodology implemented into EC8 [2] relies to some extent on the displacement modification factor, although there are some differences [3]. The equivalent linearization, for example, was considered by ATC [4] and AASHTO [5]. In this case, the underlying idea is to determine the properties of a linear elastic damped oscillator equivalent to the original inelastic one in terms of peak displacement.

The widespread use of such simplified approaches has motivated several studies, even in the last years. For example, the influence of earthquake magnitude, source-to-site distance, local soil-site conditions, ductility and hysteretic behavior on the displacement modification factor has been studied in Refs. [6,7]. The displacement modification factor has been derived in Ref. [8] for inelastic oscillators taking into account a database of Greek seismic records and, in doing so, the role of the predominant period of the ground motion was also investigated. On the other hand, the accuracy of equivalent linearization methods for the assessment of isolated bridges has been discussed in Refs. [9,10]. A large comparative evaluations among several equivalent linearization methods has been presented by Liu et al. [11], who also proposed some new formulations for the equivalent viscous damping (see for instance Ref. [12]).

Among the numerous aspects that can influence the accuracy of these simplified approaches, the occurrence of near-field earthquakes deserves special consideration. In fact, the analysis of seismic recordings at sites close to the seismic causative fault has revealed that they are characterized by large variability in the damage potential [13–15]. The main motivation is attributable to the forward directivity effect, i.e. the strengthening of the ground motion at sites along the direction of the predominant rupture propagation. This originates strong motions near the earthquake ruptures that usually exhibit a pulse-like waveform. The presence of high amplitude and long duration pulses in near-field ground motions causes significant velocity and displacement demands, thereby transmitting large amounts of energy that should be dissipated in a short time [13,16]. The performance of seismic protection devices under pulse-like waveforms (e.g., seismic isolators and tuned mass dampers) is a matter of several recent studies as well, see for instance Refs. [17–19]. In light of the peculiar effects of pulse-like waveforms on the dynamic response, specific practical and code-oriented proposals are required. Within this framework, the effects of

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pulse-like ground motions on the evaluation of the elastic spectra was addressed in Refs. [20–22]. Some studies have taken into account pulse-like waveforms on the estimation of the displacement modification factor for inelastic SDOF systems [23,24], but there are no researches (to the authors' best knowledge) that have addressed the feasibility of the equivalent linear models for such earthquake scenario.

This paper, therefore, presents some insights about the use of the equivalent linearization for inelastic (bilinear-type) SDOF systems subjected to pulse-like ground motion, a matter of practical relevance in the field of seismic isolation. In fact, base-isolated buildings behave approximately like bilinear SDOF systems under seismic base accelerations because the superstructure moves like a rigid body [11,25,26]. Similarly, base-isolated bridges can be also approximated as bilinear SDOF system [27,28], at least for preliminary evaluations. Because of the high displacement demands due to pulse-like seismic waveforms, estimating the peak displacement is very important. This can be accomplished through nonlinear time history analyses by assuming a proper hysteresis model for the base isolation system. The equivalent linearization of the corresponding approximated bilinear model, however, can be especially useful for a preliminary appraisal in order to reduce the total computational time due to the need of considering a large set of dynamic loading cases. Motivated by such practical issues, the use of the equivalent linearization for structures with known displacement ductility that behave like bilinear SDOF systems is here addressed in case of pulse-like seismic waveforms. Specifically, the accuracy of a recent equivalent linear model in predicting the peak displacement of bilinear SDOF systems under near-fault pulse-like ground motions is initially evaluated. This numerical investigation quantifies the influence of the ratio between elastic period and pulse period on the predictive capability of the considered equivalent linear model. As a consequence, a corrective factor is calibrated in order to alleviate the final linearization error for pulse-like waveforms. The main goal of this proposal is to allow the use of the same equivalent linear model for all the seismic scenarios of interest for the considered site (i.e., far-field and near-fault), provided that the obtained peak displacement predictions are properly modified for pulse-like ground motion according to the expected pulse period value.

Table 1
List of pulse-like near-fault accelerograms (M: earthquake magnitude, $\ddot{x}_g^{max}$: maximum absolute acceleration of the ground motion).

Earthquake	M	$\ddot{x}_g^{max}$ [g]	T_p [s]
Parkfield, 2004	6.00	0.6464	0.50
Coalinga-05, 1983	5.77	0.8661	0.69
San Salvador, 1986	5.80	0.8456	0.86
Coalinga-05, 1983	5.77	0.8595	0.92
San Salvador, 1986	5.80	0.4205	0.96
Parkfield, 2004	6.00	0.4373	1.02
Coyote Lake, 1979	5.74	0.4521	1.21
Morgan Hill, 1984	6.19	0.2435	1.24
N. Palm Springs, 1986	6.06	0.3291	1.55
Loma Prieta, 1989	6.93	0.4062	1.72
Bam, 2003	6.50	0.8501	2.04
Kobe, 1995	6.90	0.3229	2.06
Irpinia, 1980	6.90	0.2321	2.28
Westmorland, 1981	5.90	0.4121	2.43
Erzican, 1992	6.69	0.4864	2.65
Imperial Valley-06, 1979	6.53	0.3780	3.35
Northridge-01, 1994	6.69	0.8387	3.49
Northridge-01, 1994	6.69	0.5178	3.53
Northridge-01, 1994	6.69	0.5179	3.53
Imperial Valley-06, 1979	6.53	0.4417	3.84
Imperial Valley-06, 1979	6.53	0.1580	4.03
Imperial Valley-06, 1979	6.53	0.3754	4.05
Imperial Valley-06, 1979	6.53	0.4624	4.23
Loma Prieta, 1989	6.93	0.3627	4.47
Imperial Valley-06, 1979	6.53	0.3571	4.61
Kocaeli, 1999	7.51	0.2832	5.11
Chi-Chi, 1999	7.62	0.3331	5.15
Imperial Valley-06, 1979	6.53	0.4680	5.39
Chi-Chi, 1999	7.62	0.8218	5.74
Imperial Valley-06, 1979	6.53	0.4172	5.86
Chi-Chi, 1999	7.62	0.2207	6.45
Chi-Chi, 1999	7.62	0.1735	7.27
Chi-Chi, 1999	7.62	0.2311	8.61
Chi-Chi, 1999	7.62	0.2178	10.04
Chi-Chi, 1999	7.62	0.5621	12.17

2. Equivalent linearization of bilinear oscillators

2.1. Dynamics of a bilinear oscillator

The dynamic behavior of a bilinear SDOF oscillator subjected to seismic base acceleration is described by the following system of differential equations with zero initial conditions [29]:

$$\ddot{x}(t) + 2\xi\omega_n\dot{x}(t) + \alpha\omega_n^2 x(t) + \omega_n^2(1-\alpha)f_1(\dot{x}(t),z(t),x_y) = -\ddot{x}_g(t) \tag{1a}$$

$$\dot{z}(t) = \dot{x}(t)f_2(\dot{x}(t),z(t),x_y) \tag{1b}$$

with

$$f_1(\dot{x}(t),z(t),x_y) = z(t)f_2(\dot{x}(t),z(t),x_y) + x_y(\mathscr{U}\{z(t)-x_y\}\mathscr{U}\{\dot{x}(t)\}-\mathscr{U}\{-z(t)-x_y\}\mathscr{U}\{-\dot{x}(t)\}), \tag{2a}$$

$$f_2(\dot{x}(t),z(t),x_y) = 1-\mathscr{U}\{z(t)-x_y\}\mathscr{U}\{\dot{x}(t)\}-\mathscr{U}\{-z(t)-x_y\}\mathscr{U}\{-\dot{x}(t)\}, \tag{2b}$$

where $x(t)$ is the displacement of the oscillator relative to the ground (the upper dots indicate the time-derivative), ω_n is the circular natural frequency (the pre-yielding natural period is $T_n = 2\pi/\omega_n$), ξ is the viscous damping, $\ddot{x}_g(t)$ is the seismic acceleration at the base of the oscillator, α is the hardening ratio (ratio of the post-yield over the pre-yield stiffness), x_y is the yielding displacement (which is considered as positive numerical value) and $z(t)$ is an additional state variable. Moreover, $\mathscr{U}\{\nu\}$ is the Heaviside step function, i.e. $\mathscr{U}\{\nu\} = 1$ for $\nu \geqslant 0$ and $\mathscr{U}\{\nu\} = 0$ for $\nu < 0$. The dynamic response is symmetric. Bilinear SDOF oscillators with assigned displacement ductility will be considered. The displacement ductility is defined as $\mu = x^{max}/x_y$, where x^{max} is the maximum absolute displacement undergone by the oscillator under the base acceleration $\ddot{x}_g(t)$.

2.2. Equivalent elastic period and equivalent viscous damping formulations

Equivalent linearization methods based on the secant stiffness adopt the following definition of the equivalent elastic period T_{eq}:

$$T_{eq} = T_n\sqrt{\frac{\mu}{1+\alpha(\mu-1)}}. \tag{3}$$

The equivalent viscous damping ξ_{eq} usually consists of two contributes, namely the inherent viscous damping of the original system ξ and an additive-type term that represent the hysteretic behavior. This assumption is generally questionable from a physical standpoint. It is useful to remark in this regard that the hysteretic dissipation only is taken into account in several seismic isolation devices whereas the viscous damping is usually omitted [30,31].

A popular formulation for the equivalent viscous damping of bilinear oscillators is due to Jacobsen [32], which reads:

$$\xi_{eq} = \xi + \frac{2(1-\alpha)(\mu-1)}{\pi\mu[1+\alpha(\mu-1)]}. \tag{4}$$

It can be observed that Eq. (4) does not depend on T_n. Recently, Liu et al. [12] have modified the Jacobsen's formulation in order to improve the peak displacement prediction. On the basis of a data-driven