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Assessment of building behavior under near-fault pulse-like ground motions through simplified models

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ABSTRACT

Interstory drift and floor acceleration demands in buildings subjected to near-fault pulse-like ground motions are investigated by means of simplified building and ground motion models. A pulse model proposed by Mavroeidis and Papageorgiou is used to represent near-fault ground motions. Similarly, a continuous model formed by a flexural beam laterally coupled to a shear beam is used as a simplified model of multi-story buildings. Firstly, closed-form solutions for the response of damped single-degree-of-freedom systems subjected to Mavroeidis Papageorgiou (MP) pulses are derived and employed to construct closed-form solutions for the response of the simplified continuous model. This allows the analysis of elastic and near elastic response of buildings, which is important for the assessment of financial losses on non-structural elements. Peak responses of the continuous systems subjected to MP pulses are compared to those of the continuous systems subjected to recorded near-fault pulse-like ground motions. It is found that the proposed closed-form solutions produce very good estimates of peak interstory drift demands as well as their variation along building height. Acceleration demands are found to be more sensitive to the high frequency content of the ground motion, therefore, the results are not as good, but still MP pulses are able to capture the main features of the response when a sufficient number of modes is considered. After several parametric studies it was found that pulse duration is the most critical parameter influencing floor acceleration and interstory drift demands, when near-fault pulse like ground motion occurs; as it can induce large variations on peak and along height acceleration and drift responses.

1. Introduction

The distinct nature of near fault ground motions has been recognized for many years. Many of these ground motions are characterized by distinct high-amplitude long-duration acceleration or velocity pulses occurring primarily in the fault-normal direction. One of the first earthquakes in which pulse-like ground motions were first observed was the 1957, 4.7 M_s, Port Hueneme earthquake, [1] which caused extensive damage despite its low magnitude. The accelerogram recorded during this earthquake was characterized by essentially a single pulse with a waveform similar to the one described by Housner's dislocation theory of earthquakes [2].

Veletsos et al. [3] documented pulse-like ground motions occurring during the 1954 Eureka, California earthquake. Similarly, Housner and Trifunac [4] observed that during the 1966 Parkfield California earthquake a ground motion recorded near the fault at Cholame exhibited a transient horizontal displacement pulse occurring normal to the fault with an approximate amplitude of 10 in. and a duration of one and one-half seconds. They also noted that the 0.5 g horizontal ground acceleration recorded near the fault attenuated rapidly reducing its amplitude to one-tenth at a distance of 10 mile from the fault and also losing its pulse-like directional characteristic.

Aki [5] and Haskell [6] applied a dislocation model to study the near-field ground displacements recorded close to the causative fault. Further study of the kinematics of fault rupture processes and their influence on ground motion characteristics was provided by Boore and Zoback [7].

One of the first studies to highlight the damage potential and significance of long-duration acceleration pulses in near-fault records to earthquake resistant design was conducted by Bertero and his coworkers [8] who investigated long-duration pulses in records obtained during the 1971 San Fernando earthquake. They pointed out that these characteristic pulses were responsible for

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Symbols and acronyms

a	MP pulse phase angle
acc	acceleration
A_p	MP pulse velocity amplitude parameter
B_h	amplitude parameter of SDOF homogeneous displacement response to MP pulse ground motion
B_l	amplitude parameter of SDOF residual displacement response (after pulse occurrence)
C_1,C_2,C_3	amplitude parameters of the SDOF non-homogeneous displacement response to MP pulse ground motion
EI	flexural stiffness
f_p	predominant MP pulse frequency
g_p	MP pulse oscillatory character parameter
GA	shear stiffness
GAS	generalized acceleration spectrum
GIDS	generalized interstory drift spectrum
H	building height
IDR	interstory drift ratio
MDOF	multiple-degree-of-freedom
M_w	moment magnitude
N	number of modes considered in analysis
PFA	peak floor acceleration
SDOF	single-degree-of-freedom
t	time
T	SDOF period
T_1	first mode period
T_i	ith mode vibration period
t_o	time of epoch occurrence of the MP pulse
u_p	non-homogeneous SDOF displacement response to MP pulse ground motion
u_h	homogeneous SDOF displacement response to MP pulse ground motion
x	ratio between any level height and total building height
z	height from soil surface
α	ratio between flexural and shear stiffness
β_i	ith mode shape parameter of the coupled flexural shear beam
η_i	ith mode shape parameter of the coupled flexural shear beam
γ_i	ith eigenvalue parameter of mode i of the coupled flexural shear beam
κ	ratio of SDOF period and MP predominant pulse period ($1/f_p$)
κ_1	ratio of first mode period and MP predominant pulse period ($1/f_p$)
ξ	global damping ratio
ϕ_i	ith mode shape of the coupled flexural shear beam
ψ_1,ψ_2,ψ_3	phase angles of the SDOF non-homogeneous displacement response to MP pulse ground motion
ψ_h	phase angle of SDOF homogeneous displacement response
ψ_l	phase angle of SDOF residual displacement response (after pulse occurrence)
ω	Circular SDOF vibration frequency
ω_i	ith modal Circular vibration frequency

the extensive damage observed at the Olive View medical center during that earthquake. Anderson and Bertero [9] provided further evidence of the importance of these pulses by studying the response of multi-degree-of-freedom buildings subjected to near-fault records obtained during the 1979 Imperial Valley, California earthquake.

The 1994 Northridge and 1995 Kobe earthquakes renewed interest on near-fault ground motions and their effects on structures, yielding profuse research on the topic. In particular, several authors developed simplified representations of ground motions by studying idealized pulses (Hall et al. [10]; Alavi and Krawinkler [11]; Kostadinov and Yamazaki [12]; Makris and Chang [13] Mylonakis and Reinhorn [14]; Cuesta and Aschheim [15]; Mylonakis and Voyagaki [16], among others).

However, despite the important number of proposed analytical representations of pulse-like ground motions most have at least one of the following shortcomings: (a) represented ground motions with unrealistic waveforms (e.g., triangular, rectangular or cycloidal pulses); (b) the pulses were defined by a set of parameters that lacked a physical meaning and were unrelated to the fault rupture process; or (c) proposed pulses did not have simple mathematical representations. Menun and Fu [17] and Mavroeidis and Papageorgiou [18] addressed some of these shortcomings and proposed more realistic simplified representation to near-fault velocity pulses by using harmonic (sine) motions whose amplitude is time modulated by an exponential, Gaussian, function (Gabor wavelet) or a cosine function, respectively. By conducting regression analyses considering a large set near-fault ground motions Mavroeidis and Papageorgiou [18] developed scaling laws and calibrated pulse parameters related to the fault rupture process described according to the specific barrier model. Mavroeidis, Papageorgiou and Dong [19] noted that controlling the time variation of the amplitude of the harmonic ground motion by a harmonic modulation function had the additional advantage of allowing a closed-form solution for the response of single degree of freedom SDOF systems subjected to the synthetic ground motions, and they derived such closed-form solution for undamped systems.

Although there has been a considerable amount of work published about the response of SDOF systems to simplified analytical pulses representing near-fault ground motions, much less work has been devoted to study the response of multi-degree-of-freedom MDOF systems to analytical representations of near-fault ground motions. Several studies have shown that the effect of higher modes can be particularly important for tall buildings subjected to near-fault pulse-like ground motions [20,21]. In particular, little effort has been devoted to derive closed-form solutions to the response of MDOF systems to synthetic ground motions. Such solutions not only can provide valuable insight into the dynamic response of MDOF systems based on a small number of parameters but also permit the systematic investigation of their influence through parametric studies.

The goal of this work is to extend Mavroeidis and Papageorgiou work on the peak response of SDOF systems to pulse-like ground motions to the response of damped MDOF systems. In particular this work makes use of a simplified building model having distributed stiffness and mass. Closed-form solutions are derived allowing study of drift and acceleration demands at any point along the height of the building by changing a small number of parameters that control the ground motion and the dynamic characteristics of the structure.

2. Mavroeidis–Papageorgiou pulse model

The aim of Mavroeidis and Papageorgiou [18] work was finding a suitable way to represent near-fault pulse-like ground motions