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# Nonlinear seismic response of a gravity dam under near-fault ground motions and equivalent pulses

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## ABSTRACT

In this paper, the nonlinear seismic response of gravity dams to forward-directivity and ordinary (non forward-directivity) near-fault earthquake ground motions is investigated. Considering Pine Flat dam as case study, it is numerically modeled along with its full reservoir using the finite element method. Two sources of nonlinearity are considered in the analysis: (1) the material nonlinearity of dam concrete, and (2) the geometric nonlinearity by inserting a joint at the base of the dam. Seventy-five forward-directivity and sixty ordinary near-fault ground motions are used to obtain statistically significant results. The equivalent representative pulses of the selected forward-directivity ground motions are extracted using a well-known methodology. The dam-reservoir model is analyzed under the equivalent pulses as well to identify the cases for which the equivalent pulses can capture the structural response to the actual forward-directivity ground motions. Finally, the effects of pulse period, amplitude and energy on the seismic response of the dam-reservoir system are studied.

## 1. Introduction

High concrete gravity dams are among important infrastructures playing key role in national water and power management systems. Because of large water reservoir impounded behind a high dam, its stability and safety specifically during seismic events is of great importance. The gravity dams are typically located on rock or firm soil foundations which may contain active faults near dam sites [1]. Therefore, they may undergo near-fault earthquake ground motions; for example, Pacoima dam in the US experienced high shakings during the near-fault ground motions of San Fernando 1971, and Northridge 1994 [2,3]. The potential failure modes of gravity dams that may be triggered by an earthquake can be classified as: (1) overstressing mainly in tension, which results in cracking response of the dam body; and (2) sliding along prescribed or cracked paths specifically at the dam-foundation interface [4].

Directivity effects can considerably influence ground motions in the proximity of causative faults. The extent of near-fault region depends on earthquake magnitude. Forward-directivity results when the fault rupture propagates toward the site at a velocity nearly equal to the shear wave velocity, and the direction of fault slip is aligned with the site. This causes the wavefront to arrive as a single large pulse [5]. The forward-directivity is a dynamic phenomenon that produces no permanent ground displacement and hence two-sided velocity pulses. Most of the energy in forward-directivity ground motions is concentrated in a narrow frequency band. These motions are characterized by a distinct, high intensity velocity pulse at the beginning of time-history records, which are oriented in perpendicular direction relative to the fault plane [5]. However, not all of near-fault ground motions are pulse-type, and they may have no pulse-like characteristics.

It has been well determined that the forward-directivity pulses are critical in the analysis and design of structures in the near-fault areas. They can result in high seismic demands tending to drive structures into the nonlinear range. Typical measures such as peak ground acceleration (PGA) or spectral acceleration at periods of natural modes of structure may no longer serve as effective intensity measures [6]. The narrow band nature of the velocity pulse implies that the forward-directivity ground motions can be represented using equivalent pulse models [7–12]. The main characteristics of these pulses are: (1) pulse period, (2) pulse amplitude, (3) phase parameter, and (4) number of significant pulses [7,13]. These parameters can be determined such that the representative pulse acceptably approximates the original pulse-like motion [7]. Because the parameters of the forward-directivity pulses may control the response of structures [14–22], the effects of pulse-type ground motions should be considered in structural analysis.

Many researchers have studied the characteristics of forward-directivity ground motions [5,23,24], detecting and extracting the dominant representative pulses [7,25–27], and structural response to

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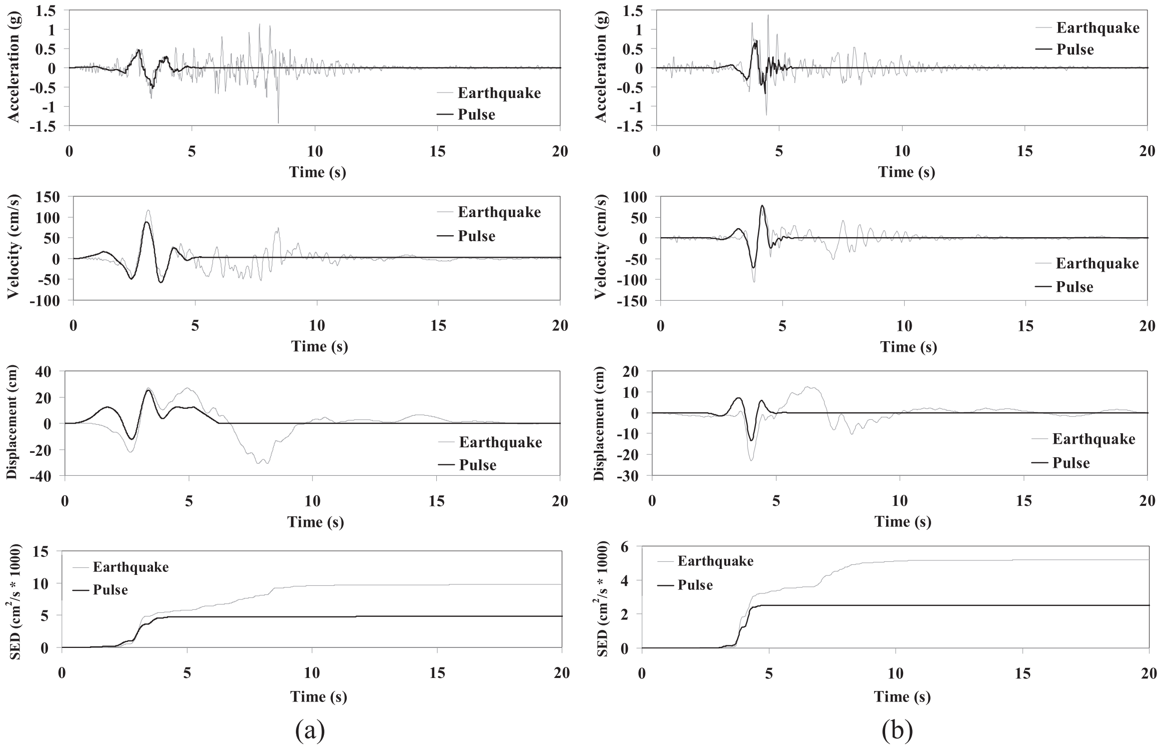


**Fig. 1.** Acceleration, velocity and displacement time-histories along with specific energy density of the actual ground motion recorded at Pacoima Dam station and its velocity pulse: (a) 1971 San Fernando earthquake, and (b) 1994 Northridge earthquake.

the actual pulse-type motions or their simplified representative pulses [14–19,28–30]. In a series of research, Bayraktar and co-workers [31–33] investigated near- and far-fault ground motion effects on the nonlinear dynamic response of various dam types such as gravity, arch, concrete faced rock-fill and clay core rock-fill dams. They have used limited number of near- and far-field ground motions for the analysis which have approximately identical PGAs. They showed that near-fault ground motions have different impacts on the dam types, and there is more seismic demand on displacements and stresses when the dam is subjected to near-fault ground motion. They also concluded that the seismic behavior of the concrete gravity dams is considerably affected from the length of the reservoir. Akkose and Seismik [34] focused on nonlinear seismic response of a concrete gravity dam subjected to near- and far-fault ground motions. The elastoplastic behavior of the dam concrete was idealized using Drucker–Prager yield criterion. They compared the seismic response of the selected concrete dam subjected to both near- and far-fault ground motions. Wang et al. [35] evaluated the effects of near- and far-fault ground motions on seismic performance of a concrete gravity dam. Four different near-fault ground motion records with an apparent velocity pulse were used. They showed the effects of near-fault ground motions on seismic performance of concrete gravity dams and demonstrated the importance of considering the near-fault ground excitations. Zhang and Wang [36] studied the near- and far-fault ground motion effects on nonlinear dynamic response of a concrete gravity dam. For this purpose, 10 as-recorded earthquake records which display ground motions with an apparent velocity pulse were selected to represent the near-fault ground motion characteristics. They found that near-fault ground motions would cause more severe damage to the dam body than far-fault ground motions. Huang [37] investigated the effects of near-fault ground motions on the nonlinear seismic response behavior of concrete gravity dams. In particular, he evaluated the characteristics of different aspects of near-fault ground motions and examined the significance of various near-fault ground motion parameters. However, still lack of specific study about the effects of forward-directivity pulses on the seismic demand analysis of gravity dams is felt.

The objective of this paper is to compare the nonlinear seismic response of a gravity dam model to forward-directivity (FD) and ordinary (non forward-directivity, NFD) near-fault ground motions. The dam is numerically modeled along with its reservoir using finite element method based on Eulerian-Lagrangian approach. Two sources of nonlinearity are considered in the analysis: (1) the material nonlinearity of dam concrete, and (2) the geometric nonlinearity by inserting a joint at the base of the dam. Seventy-five forward-directivity and sixty ordinary near-fault ground motions are used to obtain statistically significant results. The equivalent representative pulses of the selected FD ground motions are extracted using the methodology introduced by Baker [9]. The dam-reservoir model is analyzed under the equivalent pulses as well to identify the cases for which the equivalent pulses can capture the structural response to the actual FD ground motions. Finally, the effects of pulse properties, i.e. the pulse period and amplitude, on the seismic response of the dam-reservoir system are studied.

## 2. Forward-directivity ground motions and equivalent pulses

Ground motions recorded close to a ruptured fault can be significantly different from far-fault ones. The near-fault ground motions can be classified as "pulse-like" and "non-pulse-like". The pulse-like motions can be subdivide into "forward-directivity" and "fling". The specific nature of the pulse-like motion due to forward-directivity may be revealed in its velocity time-history. The peak ground velocity (PGV) of the near-fault ground motions is substantially higher than the far-fault ground motions. Previous studies about the seismic response of structures located in near-fault regions have shown that time-domain representation of the near-fault ground motions is preferable to response spectrum representation because of concentration of record's energy in a single pulse of motion [5,11,13,25].

Baker [9] described a reasonable widely-used method for quantitatively identifying ground motions containing strong velocity pulses. He employed wavelet-based signal processing to detect and extract the largest velocity pulse from a given ground motion. He also established