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Effects of near-fault and far-fault ground motions on nonlinear dynamic response and seismic damage of concrete gravity dams

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ABSTRACT

As the forward directivity and fling effect characteristics of the near-fault ground motions, seismic response of structures in the near field of a rupturing fault can be significantly different from those observed in the far field. The unique characteristics of the near-fault ground motions can cause considerable damage during an earthquake. This paper presents results of a study aimed at evaluating the near-fault and far-fault ground motion effects on nonlinear dynamic response and seismic damage of concrete gravity dams including dam-reservoir-foundation interaction. For this purpose, 10 as-recorded earthquake records which display ground motions with an apparent velocity pulse are selected to represent the near-fault ground motion characteristics. The earthquake ground motions recorded at the same site from other events that the epicenter far away from the site are employed as the far-fault ground motions. The Koyna gravity dam, which is selected as a numerical application, is subjected to a set of as-recorded near-fault and far-fault strong ground motion records. The Concrete Damaged Plasticity (CDP) model including the strain hardening or softening behavior is employed in nonlinear analysis. Nonlinear dynamic response and seismic damage analyses of the selected concrete dam subjected to both near-fault and far-fault ground motions are performed. Both local and global damage indices are established as the response parameters. The results obtained from the analyses of the dam subjected to each fault effect are compared with each other. It is seen from the analysis results that the near-fault ground motions, which have significant influence on the dynamic response of dam–reservoir–foundation systems, have the potential to cause more severe damage to the dam body than far-fault ground motions.

1. Introduction

Dams are important lifeline engineering which have contributed to the development of civilization for a long time. In order to meet the ever increasing demand for power, irrigation and drinking water etc., the majority of high concrete dams is being built or to be built in countries with active seismic activities. However, the possible failure of dams retaining large quantities of water can cause considerable amount of devastation in the downstream populated area during strong earthquakes. Dams must be completely safe and stable. The seismic safety evaluation of high dams remains a crucial problem in dam construction.

Ground motion records obtained in recent major strong earthquakes, such as Loma Prieta (1989), Northridge (1994), Kobe (1995), Kocaeli (1999), and Chi-Chi (1999), revealed unique characteristics of ground motions in a near-fault area. The seismic ground motions recorded within the near-fault region of an earthquake at stations located toward the direction of the fault rupture are significantly different from the usual far-fault ground motions observed at large distance [1]. Forward directivity and fling effects have been identified by seismologists as the primary characteristics of near-fault ground motions [2]. The fault-normal components of ground motions often contain large displacements and velocity pulses. Such a pronounced pulse does not exist in far-fault ground motions. The pulses are strongly influenced by the rupture mechanism, the slip direction relative to the site, and the location of the recording station relative to the fault which is termed as 'directivity effect' due to the propagation of the rupture toward the recording site [3–5].

Because of the unique characteristics of near-fault ground motions, the ground motions recorded in the near-fault region, which expose the structure to high input energy in the beginning of the earthquake [6], have the potential to cause a large response and considerable damage to structures. Therefore, structural response to near-fault ground motions has received much attention in recent years. The effects of near-fault ground motions on many civil engineering structures such as buildings and bridges, etc., have been investigated in many recent studies [7–17]. It can be clearly seen from these studies that the importance of near-fault

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ground motion effects on the nonlinear dynamic response of structures has been highlighted. Aseismic design of structures should be given attention to the characteristics of near-fault ground motions due to their impulsive effects on structures.

It should be noted that few studies have focused their attention on the nonlinear dynamic response and seismic damage of concrete gravity dams subjected to near-fault ground motions. For example, Akköse and Şimşek [18] studied the seismic response of a concrete gravity dam subjected to near-fault and far-fault ground motions including dam-water-sediment-foundation rock interaction. They found that plastic deformations in the dam subjected to near-fault ground motions are greater than those subjected to far-fault ground motions. Bayraktar et al. [19–22] examined the effects of near-fault and far-fault ground motions on the nonlinear response of gravity dams. The results revealed that there are more seismic demands on displacements and stresses when the dam is subjected to near-fault ground motions. Although previous studies provided some information on the effects of near-fault ground motions on the response of dams, there is no sufficient research about the near-fault ground motion effects on the seismic damage of concrete gravity dams.

In order to consider the reservoir effect on the behavior of the dam under strong ground motions, three approaches are generally used in the analyses of fluid-structure interaction problems. The simplest one is the added mass approach initially proposed by Westergaard [23] (with added masses on the dam). Another approach is the Eulerian approach [24], in which the displacements are the variables in the structure and the pressures or velocity potentials are the variables in the fluid. Since these variables in the structure and fluid are different in the Eulerian approach, a special-purpose computer program is required for the solution of coupled systems. The third way to represent the fluid-structure interaction is the Lagrangian approach [25,26], where the displacements are the variables for both the fluid and the structure approaches. For that reason, Lagrangian displacement-based fluid elements can be easily incorporated into a general-purpose computer program for structural analysis, because special interface equations are not required. Dynamic response of fluid-structure systems using the Lagrangian approach has been investigated by many researchers [18–22,27,28].

The main objective of this paper is to investigate and compare the dynamic behavior of concrete gravity dams subjected to near-fault and far-fault ground motion excitations with considering the effects of dam–reservoir–foundation interaction. The Concrete Damage Plasticity (CDP) model which includes the strain hardening or softening behavior is adopted to study the seismic response of concrete gravity dams under earthquake conditions. The 1979 Imperial Valley, 1989 Loma Prieta, 1994 Northridge, and 1999 Chi-Chi earthquake records which display ground motions with an apparent velocity pulse are selected to represent the near-fault ground motion characteristics. In this study, the term "near-fault ground motion" is referred to the ground motion record obtained in the vicinity of a fault with the apparent velocity pulse (pulse duration larger than 1.0 s), and the peak ground velocity/peak ground acceleration (PGV/PGA) value which is larger than 0.1 s. The earthquake ground motions recorded at the same site from other events that the epicenter far away from the site are employed as the far-fault ground motions, which are used to compare with near-fault ground motions. Lagrangian approach is used for the finite element modeling of dam-reservoir-foundation interaction problem. The Koyna gravity dam is employed as a numerical application. Nonlinear seismic damage analyses of the selected concrete dam subjected to both near-fault and far-fault ground motions are performed. The influence of near-fault ground motions on the dynamic response and seismic damage of concrete gravity dams is examined.

2. Characteristics of near-fault ground motions

It is well known that earthquake ground motion is a complex natural phenomenon associated with the abrupt energy release caused by fault rupture, and it is influenced by many factors, such as earthquake source mechanism, propagation path of waves, soil condition at the site, and so on. Ground motions generated from earthquakes differ from one another in characteristics, magnitude, source, distance and direction from the rupture location and local soil conditions. It has been observed that the ground motions recorded near the near-fault regions differ in many cases from those observed further away from the seismic source. Besides strong shaking, the characteristics of near-fault ground motions are linked to the fault geometry and the orientation of the traveling seismic waves [29]. The primary characteristics of near-fault ground motions are the forward directivity and fling step effects which have caused severe structural damage in recent major earthquake [2].

Directivity effects can be classified as forward, reverse, or neutral, as shown in Fig. 1. The effects of forward directivity are generated when the rupture front propagates toward the site and the direction of slip on the fault is aligned with the site. As the rupture often propagates at a velocity close to the velocity of shear wave radiation, energy is accumulated in front of the propagating rupture and is expressed in the forward directivity region as a large velocity pulse [30]. Forward directivity effects can be presented both for strike-slip and dip-slip events. In strike-slip events, forward directivity conditions are typically largest for sites near the end of the fault when the rupture front is moving towards the site. In dip-slip events, forward directivity conditions occur for sites located in the up-dip projection of the fault plane [5]. If the rupture propagates away from the site, the site is likely to demonstrate reverse directivity, and the motion is characterized by longer duration and lower amplitude ground motions. Neutral directivity occurs when the site is more or less perpendicular to the fault from the hypocenter. The phrase "directivity effects" usually refers to "forward directivity effects", as this case results in ground motions that are more critical to engineering structures.

Fling step is a result of a permanent ground displacement due to the static deformation field of the earthquake, occurring over a discrete time interval of several seconds as the fault slip is developed [31]. This phenomenon is characterized by a unidirectional large amplitude velocity pulse and a discrete step in the displacement time history [32] that occurs parallel to the strike of the fault with strike-slip earthquakes and in the dip direction for dip-slip events.

3. Near-fault and far-fault ground motion records considered in this study

One of the most important characteristics of near-fault events concerning the field of structural and civil engineering is the

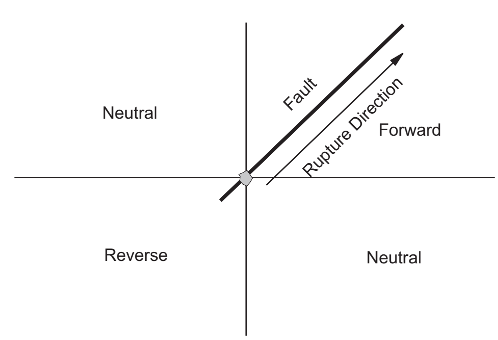

Fig. 1. Defining a site as forward, reverse, or neutral directivity [32].