Soil Dynamics and Earthquake Engineering 98 (2017) 235–243

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Seismic failure analysis for a high concrete face rockfill dam subjected to near-fault pulse-like ground motions

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ARTICLE INFO

Keywords:
Near-fault
Pulse-like ground motion
Concrete face rock fill dam
Dynamic elastoplasticity

ABSTRACT

In the strong seismic zone of Western China, many high concrete face rockfill dams (CFRDs) have been built or designed, and some of these high dams are located in the near-fault region. A near-fault earthquake has relatively long velocity and displacement pulse periods, and a dynamic directivity effect could result in dam failure. However, there are few seismic analysis of high CFRDs considering pulse-like effect. Therefore, it is necessary to investigate the dynamic response of high CFRDs in the near-fault area. In this study, 16 ground motions are selected including 8 pulse-like motions with rupture forward directivity effects and 8 non-pulse motions. The rockfill materials are described using a generalized plasticity model, while a plastic damage model that considers stiffness degradation and strain softening is used to simulate the face slabs. Furthermore, the interfaces between the face slabs and cushions are modeled using interface elements that follow a generalized plasticity model to describe the relative sliding between slab and rockfill.

The numerical analysis results indicate that although the near-fault pulse-like ground motion has a moderate impact on the dam acceleration, it has a remarkable impact on the residual deformation of dam and concrete slab damage, especially for the dam crest. The seismic response of the dam increases with an increasing ratio of the peak ground velocity to the peak ground acceleration (PGV/PGA). In addition, even with the similar Arias intensity, the residual deformation of the dam under pulse-like records is larger than those under non-pulse ones. The pulse-like ground motion often generates a high input energy which will cause large deformation of concrete face slab in a short period of time. Therefore, when a CFRD is constructed in the vicinity of an earthquake, the effects of the pulse-like ground motion should be investigated to comprehensively evaluate the seismic safety of the dam.

1. Introduction

In the strong seismic zone of western China, many concrete face rockfill dams (CFRDs) with heights over 200 m have been built or designed [1]. Some of these high dams are located in the near-fault region, such as the Zipingpu CFRD. Generally speaking, near-fault ground motions are referred to the ground motions of site within a distance of about 20 km from the rupture fault, which is significantly different from those at the far-fault region [2–5]. Malhotra [6] demonstrated that a response spectrum with a high ratio of the peak ground velocity to the peak ground acceleration (PGV/PGA) has a relatively wide range of acceleration sensitivity. The near-fault pulse-like ground motions have large long-duration velocity and displacement pulse, and large peak ground acceleration (PGA) especially in the fault-normal direction, which are mainly resulted from the effect of rupture directivity and hanging wall thrusting [5]. Owing to the above characteristics, near-fault ground motions can cause severe damage to engineering structures [2]. The near-fault pulse-like ground motions present a serious challenge in the seismic safety evaluation of dams.

The 1979 Kings Valley earthquake, the 1994 Northridge earthquake, the 1999 Chi-Chi earthquake and the 2008 Wenchuan earthquake revealed unique characteristics of ground motions in near-fault areas [3,5,7]. These near-source outcomes cause most of the seismic energy from the rupture to arrive in a single coherent long-period pulse of motion [8]. The pulses are strongly influenced by the rupture mechanism, including the slip direction relative to the site and the location of the recording station relative to the fault. It is termed as 'directivity effect' due to the propagation of the rupture toward the recording site [2,7]. The pulse-like ground motions are caused primarily by the forward directivity effect, which are observed at a site when

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http://dx.doi.org/10.1016/j.soildyn.2017.03.031
Received 24 October 2016; Received in revised form 28 March 2017; Accepted 29 March 2017

the fault rupture propagates toward the site with a velocity close to shear wave velocity [9].

So far, many studies have focused their attention on the dynamic response and seismic damage of CFRDs subjected to the ground motions without considering pulse effect. Mejia [10] made a comparison between the results of three-dimensional and two-dimensional dynamic analyses of two dams with different canyon geometries. Uddin and Gazetas [11] analyzed the response of a typical 100-m-tall CFRD under strong seismic shaking. Uddin [12] shown that slab distress may be produced only from axial tensile forces, developing mainly due to the rocking component of dam deformation. Hacıefendioğlu et al. [13] investigated seismic response of CFRD subjected to spatially varying ground motions, considering dam-reservoir-foundation interaction systems. Kong [14] and Zou [14] analyzed the major factors affecting dislocation displacement of face-slabs of the Zipingpu dam during the Wenchuan earthquake. In addition, Bayraktar [15] and Xu [16] investigated the distribution of the hydrodynamic pressure and its effect on the dynamic stress in the face slabs. The numerical results mentioned above are mainly obtained by the equivalent linear model for rockfill and linear elastic model for the face slab [10–14,16,17]. Elgamal et al. [18] used a multi-field surface model based on the incremental theory of plasticity to analyze the observed deformation and acceleration responses of the La Villita Dam. Zou et al. [19] shown that a 3D finite element procedure based on a generalized plasticity model is suitable to evaluate the dynamic responses of CFRDs during strong earthquakes. Meanwhile, several elastoplastic models of concrete have been established based on damage mechanics and used to simulate the damage process and the mechanism of concrete structures [20–26]. As for concrete slab, the Drucker-Prager model was used in nonlinear analyses for concrete slab in Bayraktar [15]. Arici et al. [27] examined the cracking behavior of the slab of a CFRD over its life cycle. Xu et al. [28] revealed the main tensile damage positions and areas of weakness in the slabs under strong earthquake. These researches indicated that the nonlinear behaviors of rockfill and concrete slab have significant influence on the dynamic safety of CFRDs.

However, it should be noted that there are few studies related to the dynamic failure for a high CFRD with the elastoplastic model for rockfill and the plastic-damage constitutive law for concrete slab simultaneously. Furthermore, the current investigations about hydraulic structure subjected to pulse-like ground motion focused primarily on the gravity dam [29–35]. There have been few researches on dynamic failure for CFRDs subjected to pulse-like ground motion. Thus, the pulse-like ground motion effects on the seismic failure of CFRDs is still unknown.

The main objective of this paper is to investigate and compare the dynamic behavior of CFRDs subjected to pulse-like and non-pulse ground motion. The systematic non-linear dynamic failure analysis for a 200-m CFRD is performed using GEODYNA, which developed by the first author [17,19,36]. The proposed and implemented models of relevant literatures are applied to the analysis for CFRD failure mechanism under pulse-like ground motions. The rockfill materials are described using a modified generalized plasticity model which can be used to evaluate the seismic residual deformation of the dam [14,37]. The interfaces between the face slabs and cushions are modeled using a generalized plasticity model to describe the relative sliding between slab and rockfill [38]. A plasticity damage model that considers stiffness degradation and strain softening is used to simulate the face slabs [28].

2. Selection of ground motion time history

Generally, the large ratios of PGV/PGA of ground motions imply that these records could contain velocity pulses, and for the non-pulse ground motions the ratios of PGV/PGA are usually smaller than 0.20 [30]. There are only a limited ground motion records worldwide for earthquakes greater than magnitude 7.0 within distance less than 20 km from causative fault. The Chi-Chi earthquake produced a fairly complete near-fault strong motion dataset. The 16 near-fault ground motions are chosen, these motions include 8 pulse-like ground motions with a rupture forward directivity effect and 8 non-pulse records, as shown in Table 1. The data are obtained from the database of Pacific Earthquake Engineering Research Center (PEER) [39]. The closet distance to rupture these records is smaller than 20 km, whereas PGA is larger than 0.1 g and PGV is greater than 30 cm/s.

Table 1
Properties of selected near-fault and far-fault ground motions considered in this investigation.

Ground motions	Station		d (km)	PGA (g)	PGV (cm/s)	PGV/PGA	$I_{0.3\,g}$ (m/s)
	No.	Name					
Pulse-like	1	TCU068	1.09	0.566	177	0.31	0.96
	2	TCU102	1.79	0.298	112	0.38	2.1
	3	TCU054	4.64	0.148	59	0.40	3.7
	4	TCU052	5.73	0.346	159	0.45	2.18
	5	TCU120	8.10	0.225	63	0.28	3.51
	6	CHY025	18.79	0.159	48	0.30	4.08
	7	TCU075	1.49	0.333	88	0.27	2.47
	8	TCU082	5.73	0.223	58	0.26	2.21
Non-pusle	9	CHY041	19.83	0.303	18	0.06	2.21
	10	TCU071	4.88	0.567	44	0.08	2.69
	11	TCU070	19.10	0.255	52	0.20	3.07
	12	TCU078	7.50	0.444	39	0.09	2.74
	13	TCU065	0.98	0.814	126	0.15	2.21
	14	TCU079	10.04	0.742	61	0.08	1.30
	15	TCU089	8.22	0.333	31	0.09	2.52
	16	TCU072	7.08	0.489	72	0.15	2.21

The pulse-like ground motion has noticeable long-period acceleration and velocity pulses and thus produces larger ground displacement. As illustrated in Figs. 1–3, two records collected form TCU052 (pulse-like) and TCU071 (non-pulse) stations are normalized to have a peak ground acceleration (PGA) equal to $0.3g$. The peak velocity and displacement of the pulse-like motion is 6.6 and 22.7 times that of the non-pulse motion, respectively.

The 16 ground motions are formulated using the code spectrum of the specifications for the seismic design of hydraulic structures in China [40] as shown in Fig. 4. The results show that the mean acceleration amplification factors induced by pulse-like ground motions are similar to the non-pulse ones in short period. $I_{0.3g}$ is the Arias intensity [41] of the ground motions with peak accelerations adjusted to 0.3 g.

3. Constitutive model

3.1. General plasticity model for the rockfill [42–45]

The elastic-plastic matrix is defined as

$$\mathbf{D}^{ep} = \mathbf{D}^{e} - \frac{\mathbf{D}^{e}\colon \mathbf{n}_{gL/U} \otimes \mathbf{n}\colon \mathbf{D}^{e}}{H_{L/U} + \mathbf{n}\colon \mathbf{D}^{e}\colon \mathbf{n}_{gL/U}} \tag{1}$$

The elastic behavior is defined by the shear and bulk moduli:

$$G = G_0 p_a (p/p_a)^{m_s} \tag{2}$$

$$K = K_0 p_a (p/p_a)^{m_v} \tag{3}$$

The flow direction vector in triaxial space is defined as:

$$\mathbf{n}_{\mathrm{gL}}^{\mathrm{T}} = (n_{\mathrm{gLv}}, n_{\mathrm{gLs}}) \tag{4}$$

where $n_{\mathrm{gLv}} = \frac{d_{\mathrm{g}}}{\sqrt{1+d_{\mathrm{g}}^2}}$, $n_{\mathrm{gLs}} = \frac{1}{\sqrt{1+d_{\mathrm{g}}^2}}$, and $d_{\mathrm{g}} = (1+\alpha_{\mathrm{g}})(M_{\mathrm{g}} - \eta)$.

Non-associated flow rule is assumed in the model and the loading direction vector is defined as:

$$\mathbf{n}^{\mathrm{T}} = (n_{\mathrm{v}}, n_{\mathrm{s}}) \tag{5}$$