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Seismic performance investigation of high CFRDs subjected to mainshock-aftershock sequences

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ABSTRACT

In this paper, 24 as-recorded mainshock-aftershock seismic sequences are selected to analyse the seismic performance of a 200-m-high concrete face rockfill dam (CFRD) subjected to mainshock-aftershock seismic sequences by a series of elastic-plastic analyses, based on three damage measures (DMs), displacement, shear strain and damage index (DI). The dynamic responses of CFRD subjected to single mainshocks and single aftershocks are also obtained for comparison. Evidently, CFRD will experience additional damage or destruction while experiencing an aftershock, which cannot be ignored in the corresponding seismic design codes.

1. Introduction

According to previous studies, earthquakes typically consist of foreshocks, mainshocks, and aftershocks. Moreover, strong aftershocks are usually unpredictable and seriously threaten the security of standing structures [1]. After the mainshocks, structures will not usually exhibit significant damage; however, aftershocks may badly damage or even completely destroy the existing structures. Therefore, the dynamic response of dams under the action of seismic sequences and the cumulative damage that high CFRDs sustain must be investigated. In China, nearly 300 CFRDs are either under construction or already built, and most of these dams are located in earthquake-prone regions [2]. Some scholars have investigated their seismic performance under earthquakes. For example, Xu et al. [3] conducted a dynamic damage analysis in consideration of the non-uniformity of concrete in the concrete slabs of CFRDs. Furthermore, Pang et al. [4] quantitatively analysed the seismic fragility of a CFRD using deformation and damage indices. However, mainshock-aftershock seismic sequences are often overlooked during the nonlinear dynamic analysis of CFRDs, and no investigations have been conducted on the seismic performance of high CFRDs subjected to mainshock-aftershock sequences.

This paper analyses the seismic performance of CFRDs under the action of mainshock-aftershock seismic sequences by employing three damage measures (DMs), displacement, shear strain and DI [4,5], which constitute the main aspects corresponding to deformation, dam slope stability and face slab safety, respectively. Moreover, a series of elastic-plastic analyses are performed to describe the nonlinear behaviour of the rockfill materials and concrete face slabs.

2. Seismic sequences and constitutive model

In this paper, the seismic sequences are similar to those reported in the article by Wang [6] and the detailed ground motion information is obtained from PEER and COSMOS. The seismic sequences are selected according to the following criteria: (a) the magnitude of the mainshock is no less than 5.5, and that of the aftershock is no less than 4.0; (b) the seismic sequences originate from free fields or low-rise buildings; and (c) the ratio of the peak acceleration of the aftershock to the peak acceleration of the mainshock is no less than 0.7. To ensure that the structures have sufficient time to maintain equilibrium prior to subsequent ground motions, a 10-s interval between two seismic events is used for each seismic sequence. The peak acceleration of the mainshock is scaled to 0.4 g, and the aftershock is adjusted according to the scaling of the mainshock.

A generalized plasticity model was modified [7] to describe the nonlinear behaviour of rockfills, and a generalized plasticity interface model [8] was proposed to simulate the characteristics of the interface between the face slabs and cushion. Furthermore, the plastic-damage model proposed by Lee et al. [9] is employed in this paper to describe the damage behaviour of concrete face slabs.

3. Numerical model

As shown in Fig. 1, the height of the 2-D finite element model of the

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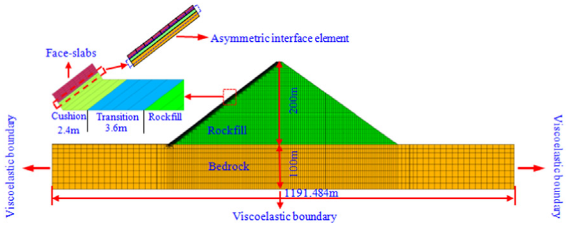

Fig. 1. 2-D finite element mesh of CFRD.

CFRD is 200 m, and the top width of the dam is 13 m. The upstream and downstream dam slopes are 1:1.4 and 1:1.5, respectively. The water level is 180 m, and an added mass method [10] is used to simulate the hydrodynamic pressure of the concrete face slabs. A viscous-spring boundary combined with an equivalent nodal loading [11] is used to simulate the interaction between the dam and bedrock, and the ground motion inputs are added in this form. The interface between the face slabs and cushions are simulated with an asymmetric interface proposed by Qu et al. [12] based on the Goodman element. The parameters of rockfill materials and interface are obtained from the literature [13] and the parameters of face slabs come from [3].

4. Results and discussion

In this study, the displacement of the dam crest is recorded. The displacement time history of the dam crest under a typical event selected from the 24 as-recorded seismic events is shown in Fig. 2 (the X and Y displacements represent the horizontal and vertical displacements, respectively). Fig. 2 shows that the nonlinear responses of the dam to the seismic sequence and a single aftershock exhibit a significant variation. The aftershock will cause the residual displacement of the mainshock to increase during the seismic sequence (on both the horizontal and the vertical displacement), and the increase in the vertical displacement is more obvious; therefore, compared with a single mainshock, the seismic sequence will cause the dam to exhibit larger deformations. Fig. 3 summarizes the horizontal and vertical displacements at the dam crest under different as-recorded seismic sequences. On average, the horizontal and vertical displacements caused by aftershocks to the mainshock-damaged dam were approximately 48% and 42% lower, respectively, than those to the undamaged dam. This finding also indicates that the displacements caused by mainshock-aftershock sequences are not simply the sum of the displacements generated from a single mainshock and a single aftershock. The additional deformation caused by the aftershock is more significant to the vertical displacements. Moreover, the displacement caused by a single mainshock to the dam may occasionally be smaller than that caused by a single aftershock.

The time histories of the shear strain of the dam are shown in Fig. 4. The shear strain waveforms of the mainshock and aftershock are considerably different, but a sudden increase in the shear strain occurs at some point during both the mainshock and the aftershock. The characteristics of the fluctuations between the shear strain and horizontal displacement are similar; the shear strain will drop during the initial part of the aftershock and fluctuate around a certain value for a period of time. In the first 5 s of the mainshock, the shear strain changes only slightly; after some time, however, it changes significantly. In addition, Fig. 4 shows that the additional shear strain induced within the dam by the mainshock-aftershock sequence is not equivalent to the shear strain generated by the single aftershock in comparison with the mainshock. Fig. 5 shows the shear strain of the dam under different as-recorded seismic events. The mean values of the shear strain of the dam under single mainshock events, single aftershock events and seismic sequences are 1.14%, 1.00% and 1.28%, respectively. In the mainshock-aftershock seismic sequences, the additional shear strain generated by the aftershocks is only 0.14%, but the shear strain gained by the single aftershocks is 1%. When the dam has been subjected to a mainshock, the increase in the shear strain of the dam caused by the aftershock will be smaller, which indicates that the mainshock has a considerable influence on the shear strain of the dam caused by a strong aftershock.

The time history of the DI under a mainshock-aftershock seismic sequence is plotted in Fig. 6. As shown in the figure, the DI will not instantaneously rise immediately after the face slab has been subjected to the mainshock, and will not change over a short period of time. As the mainshock continues, the DI will increase slowly, after which it will suddenly increase and grow to a relatively large level. Then, during the subsequent 10-s recovery period, the DI is constant. Fig. 7 shows the DI under single mainshocks, seismic sequences and single aftershocks. Mainshock-aftershock seismic sequence can cause more damage to the face slab overall than a single mainshock. On average, the DIs under seismic sequences, single mainshocks, and single aftershocks are 0.253, 0.237 and 0.129, respectively. In most cases, a single aftershock causes less damage to the face slab than a single mainshock. However, during some seismic events, the aftershock causes more damage to the face slab than the single mainshock and even the seismic sequence. Furthermore, the undamaged dam shows a greater sensitivity to aftershocks than the damaged dam. Compared with the aftershock in the mainshock-aftershock seismic sequence, a single aftershock will cause greater damage to the dam, indicating that the cumulative damage caused by a single mainshock and a single aftershock to the dam is not linearly related to the damage experienced by the dam caused by the mainshock-aftershock seismic sequence. Moreover, the damage caused by the mainshock will have a certain influence on the response of the dam to the aftershock, that is, it can decrease the amount of damage to the dam caused by the aftershock.

5. Conclusions

This paper studies the influences of mainshock-aftershock seismic sequences on the deformation, dam slope stability and face slab damage of a high CFRD. The seismic performance of the dam under the action of a single aftershock is also analysed. The following conclusions can be

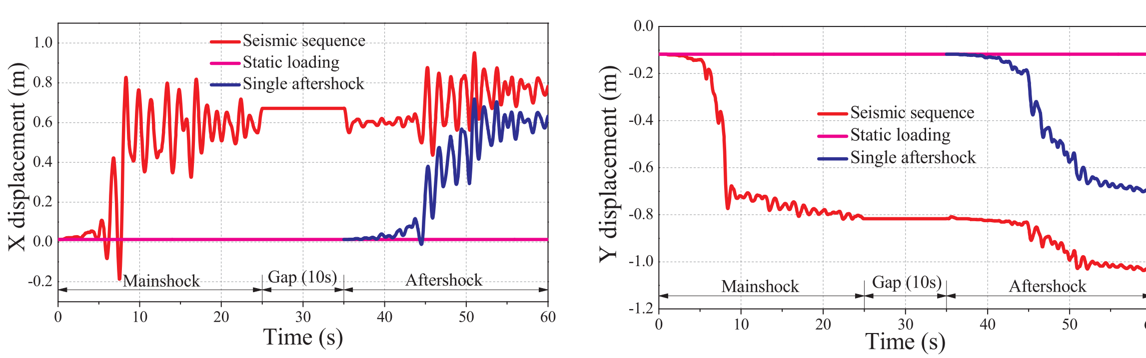

Fig. 2. Horizontal displacement and vertical displacement at the dam crest for a selected seismic sequence (Cape Mendocino/Petrolia, Station: 1023-Comp. 360).

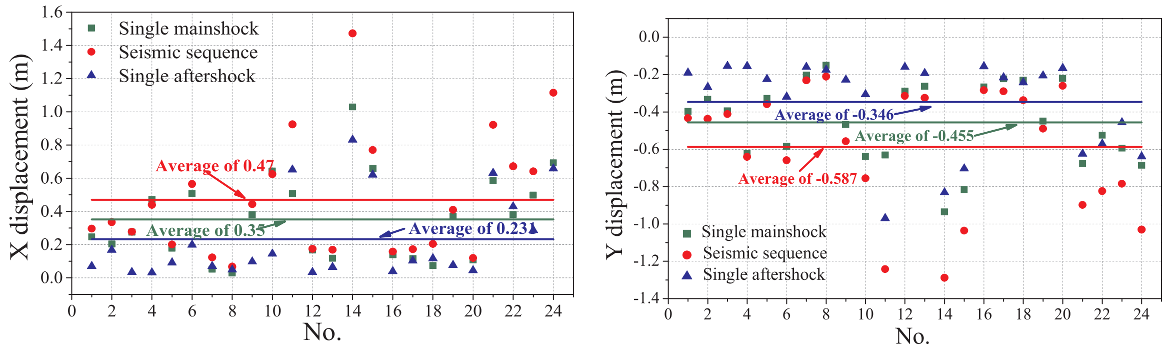

Fig. 3. Deformation at the dam crest under different as-recorded seismic events.

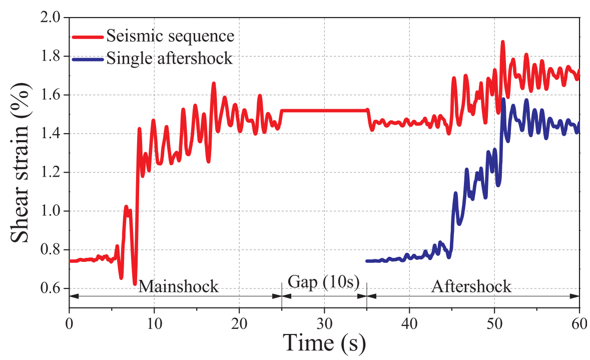

Fig. 4. Shear strain of the dam under a typical seismic event (Cape Mendocino/ Petrolia, Station: 1023-Comp. 360).

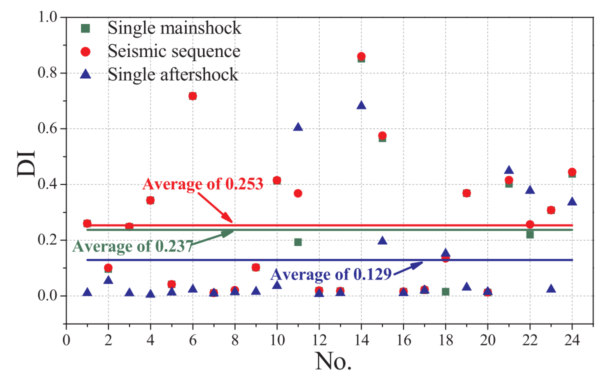

Fig. 7. DIs for the face slab under different as-recorded seismic events.

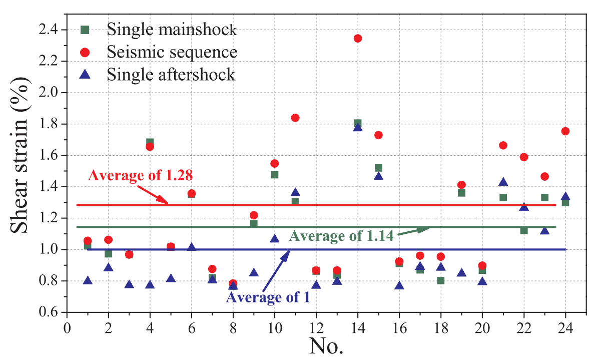

Fig. 5. Shear strain of the dam under different as-recorded seismic events.

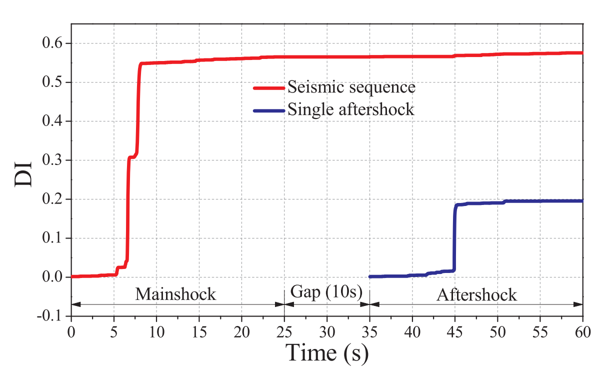

Fig. 6. DI of the face slab under a typical seismic event (Cape Mendocino/ Petrolia, Station: 1023-Comp. 360).

drawn through the above findings:

(1) Mainshock-aftershock seismic sequences can cause more damage to high CFRDs than a single mainshock. The deformation and shear strain increase considerably under mainshock-aftershock seismic sequences. However, in most cases, a mainshock-aftershock seismic sequence does not greatly increase the DI compared with a single mainshock. Furthermore, the face slab damage caused by a single aftershock to an undamaged dam may be larger than the damage caused by a single aftershock to a corresponding mainshock-damaged dam and even greater than the damage caused by a seismic sequence.

(2) The different damage index interacts and one of them might reach or exceed the limit state during aftershock. A single mainshock and a single aftershock have a striking contrast to the damage of the dam. The different ground motion characteristics between a single mainshock and a single aftershock may contribute to this result.

(3) The results show that seismic sequences can lead to more damage and destruction to a high CFRD compared with a single seismic event. Seismic design codes that consider only a single earthquake will consequently underestimate the damage to a dam caused by multiple earthquakes. Therefore, it is necessary to consider the impacts of seismic sequences in the seismic design codes of CFRDs in the future.

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