Response to discussion of "Seismic damage analysis due to near-fault multipulse ground motion"

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Abstract

The authors thank the discusser for the attention and interests on our previous work, entitled "Seismic damage analysis due to near-fault multipulse ground motion" (referred to as the original paper/work in the following text). To demonstrate the increased seismic demands required by multipulse ground motions compared to non- and single-pulse ground motions, three cases were illustrated in the original work, including frame structures, a soil slope and a concrete dam. The discusser, Dr. M.Amin Hariri-Ardebili, raised concerns on the seismic response of the dam, together with the optimal intensity measure of ground motions. Specifically, four sub-issues are involved, including effectiveness of the numerical model of dam, the damage index for dam, the selection strategy for input ground motions, and the ground motion intensity measures. Detailed responses to these issues are provided. In short, the main conclusion in the original paper that the multipulse ground motions potentially cause more severe damage compared to non- and single-pulse ground motions is reliable.

Keywords: multi-pulse ground motion, near-fault earthquake, pulse-like ground motion, seismic damage analysis, response spectrum, seismic risk

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1. Summary of the discussion

Regarding to the authors' original paper [1], the discusser raised two questions: the seismic response of the dam and the optimal intensity measure [2]. The effectiveness of the numerical model for dam and the evaluation parameter for dam damage are discussed in the context of the seismic response of the dam. Two sub-issues are related to ground motions: the PGA-based scaling method and the optimal ground motion intensity measure. Four specific issues are summarized as follows.

(1) Effectiveness of the numerical modeling for Koyna Dam. The discusser stated that the results are questionable due to the simplification of the coupling system, including the dam-reservoir interaction, the dam-foundation interaction, and the boundary condition of the numerical model.

(2) Reliability of dam damage index. The discusser introduced some damage indices and stated that the global damage index for the dam in the original paper is inappropriate since the element sizes may differ by up to ten times.

(3) Effectiveness of the PGA-scaling method for input ground motions. The discusser stated that the PGA-scale method is out-of-date. The selection strategy from ground motion databases should be adopted for input ground motions.

(4) Ground motion intensity measure. The discusser stated that Figure 15 in the original paper is questionable since the probabilistic seismic demand model, which is able to connect ground motion intensity measures and engineering demand parameters, is not performed. The discusser also expressed concerns on the unscaled Arias intensity, the dam fundamental period, and seismology attributes.

2. Authors' responses

2.1. Numerical model validation

A comparative study was conducted to validate the effectiveness of the numerical model. Specifically, simulations were performed based on the numerical model presented in the original paper and the on-site seismic record near the Koyna Dam. Subsequently, the simulated results were compared with the actual damage observed on the site, as documented by Chopra and Chakrabarti [3], and with previous numerical research conducted by Lee and Fenves [4].

The seismic records near the Koyna Dam at horizontal and vertical directions are shown in Figure 1, and are simultaneously input into the numerical model of the dam. The maximum plastic strain and tensile damage variables at different time are depicted in Figures 2 and 3, respectively.

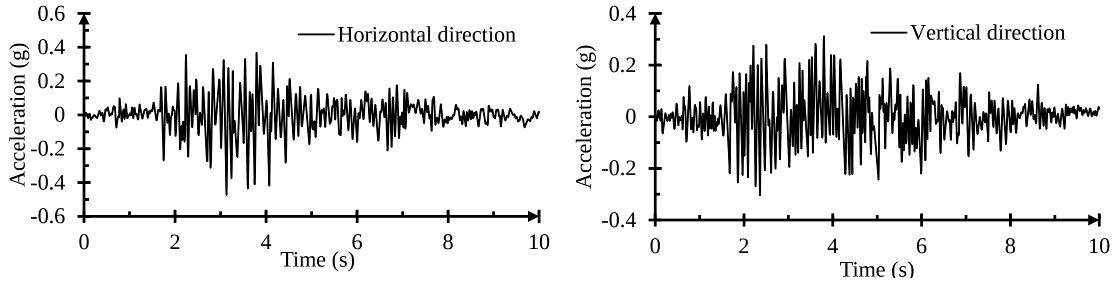
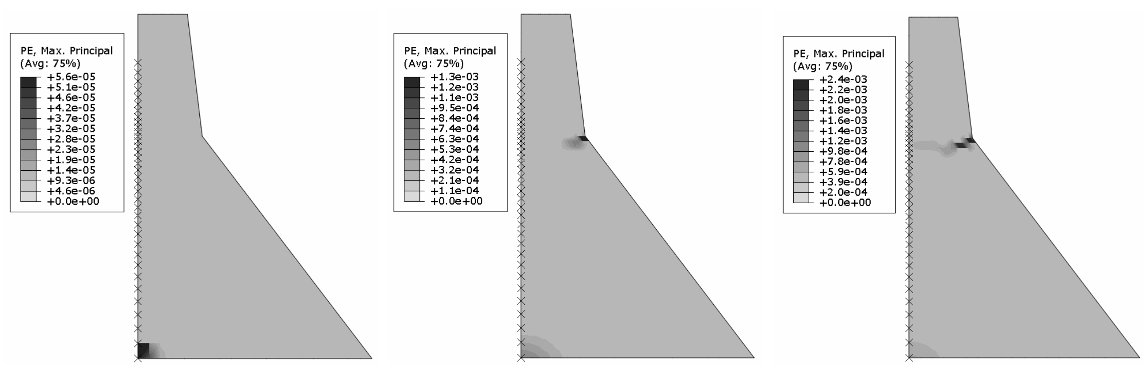


Figure 1: On-site seismic record near Koyna Dam

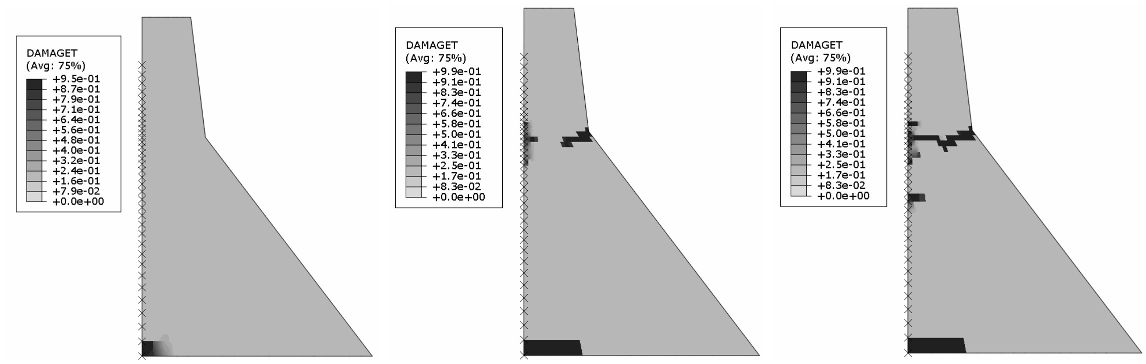


(a) (b) (c)

Figure 2: Maximum plastic strain of dam under on-site seismic record at (a) $t = 2.7$ s, (b) $t = 4.5$ s, and (c) $t = 10$ s.

Figure 2 illustrates that the maximum plastic strain initially appears at the bottom of the dam. Subsequently, the maximum plastic strain predominantly occurs at the neck of the dam. The direction of maximum plastic strain aligns with the direction of cracking, indicating that the primary cracking in the dam occurs at the neck. Combining the information on tensile damage in Figure 3, while the maximum plastic strain at the bottom of the dam does not continuously increase, there is noticeable tensile damage at the bottom. Hence, we could summarize that the primary damage areas are located at the bottom and neck of the dam, which aligns closely with the actual dam damage observed on the site [3].

Furthermore, the tensile damage failure pattern obtained from the numerical model in this study (see Figure 3) aligns with the results in Lee and Fenves [4]. Hence, the numerical model



(a) (b) (c)

Figure 3: Tensile damage variable of dam under on-site seismic record at (a) t = 2.7 s, (b) t = 4.5 s, and (c) t = 10 s.

established in original paper is deemed reliable overall, and results in the original paper based on this model are considered effective.

Therefore, we may not establish a very detailed model for the dam; however, the model in the original paper is capable of capturing the key behavior of the dam. Especially, the main objective of the original paper is to compare the seismic responses under non-, single-, and multi-pulse ground motions, rather than to evaluate the seismic response of the dam in detail. With this focus, the model in the original paper is sufficient to support the comparative results among non-, single, and multi-pulse ground motions.

2.2. Evaluation parameters for dam damage

The authors thank the discusser for pointing out the difference of element sizes in the model. To alleviate the influence of this issue, a different measure based on image pixels of the damage contour rather than the amounts of model elements, is adopted herein. Specifically, the area where tensile damage variable is greater than 0.8 is utilized as the index to evaluate the global damage of dam. An example of calculating the damage area pixels is presented in Figure 4.

The crest displacement of the dam is also considered, as suggested by the discusser in the discussion paper. The boxplot of the updated global damage index and crest displacement is presented in Figure 5. The results align with the findings in Figure 15 of the original paper, indicating that multipulse ground motions potentially result in more severe damage to the dam compared to non- and single-pulse ground motions.

Numerous damage indices for dams have been proposed in previous works, as mentioned by the discusser. Testing all of them is impractical and unnecessary. Based on the damage indices used

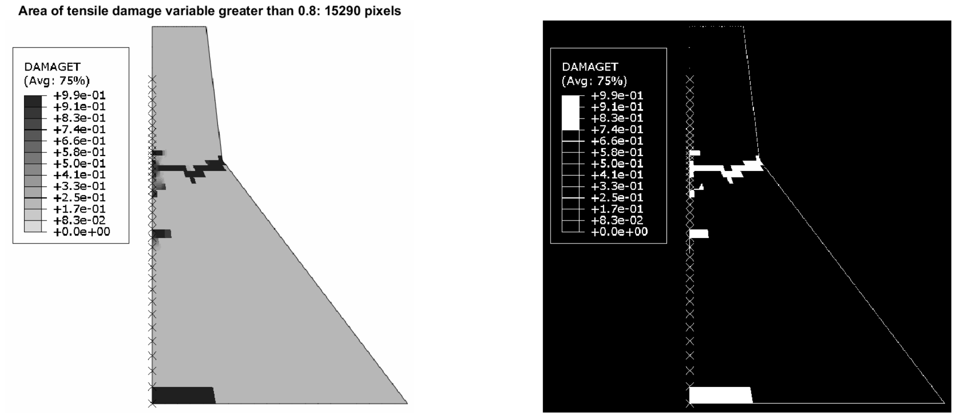


Figure 4: Example of the global damage index using the pixels of the tensile damage contour, where the white area in the right diagram represents the region under consideration.

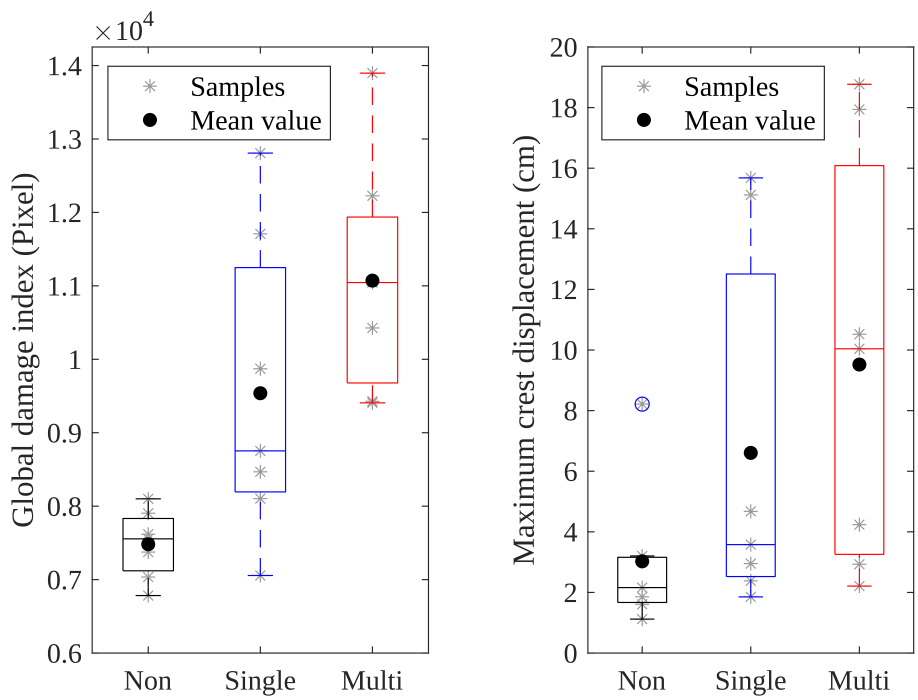


Figure 5: Boxplot about the global damage index (left) and the maximum crest displacement (right) of the dam subjected to non-, single-, and multi-pulse ground motions.

in the original work and this study, both local and global damage characteristics of the dam have been well evaluated. Therefore, the conclusion that the dam under multipulse ground motions potentially increase the seismic demands remains reliable.

2.3. Ground motion selection strategy

The authors agree that a selection strategy, such as the response spectrum method [5] or conditional mean spectrum-based methods [6], could result in a more reliable comparison among non-, single, and multi-pulse ground motions. However, the selection strategy requires a reliable database that contains sufficient multipulse ground motions. However, no databases for multipulse ground motions are available currently. As the authors mentioned in the Discussion section of the original paper, 'this study does not comprehensively consider the randomness of ground motions limited by the amounts of multipulse records. However, the effects of the stochastic property of ground motion should be considered to summarize more universal conclusions.' Hence, the spectra-based selection methods is of practical difficulties in the present study.

Since all the ground motions are from the same earthquake, the Chi-Chi, Taiwan Earthquake, it may be advantageous for the comparison among non-, single-, and multi-pulse ground motions. Besides, the PGA-scaling method is used since it is the most common method employed in previous researches.

2.4. Ground motion intensity measures

The probabilistic seismic demand model is a comprehensive framework for estimating the seismic risk. For example, four phases (i.e., hazard analysis, structural analysis, damage analysis, and loss analysis) are involved in performance-based earthquake engineering [7], where ground motion intensity measures serve as parameters connecting seismic hazard analysis and structural analysis. Fragility functions are usually performed to connect intensity measures with engineering demand parameters [8].

The discusser stated that an optimal intensity measure that could effectively characterize multipulse ground motions should be defined and then applied to establish connection with the damage index of the dam. The authors do agree that relevant work in this direction is of significance. Fragility functions could also help in further understanding the effects of near-fault multipulse ground motions on the dam. However, this falls outside the scope of the original paper. The primary objective of the original work is to 'facilitate recognizing the potential of near-fault multipulse ground motions on structural damage compared to non- and single-pulse ground motions.' Furthermore, a sufficient number of multipulse records are required for reliable fragility functions. Thus, probabilistic seismic demand model should be conducted in subsequent stages after the potentially increased seismic demands caused by multipulse ground motions are identified (i.e., the objective of the original paper), and a sufficient number of multipulse records becomes available. Therefore, the optimal ground motion intensity measure is not discussed in the original work.

Regarding the Arias intensity, the authors agree that the normalized and original Arias intensity of ground motions vary. However, the original paper aims to discuss the significant duration of different ground motions, and does not involve the optimal intensity measures as explained above. Hence, the normalized Arias intensity is used in the original work.

Concerning the fundamental period, while the authors did not further investigate the effects of the fundamental period of the dam, a comprehensive examination of the effects of fundamental period was conducted in the case of frame structures. The results indicate that multipulse ground motions potentially increase seismic demands, irrespective of varying structural fundamental periods.

Regarding seismological attributes, the authors mentioned this in the original paper's Discussion section. 'This study does not encompass the seismological mechanism of multipulse ground motion generation. However, this is another essential component to further broaden the application of multipulse records.'

3. Concluding remarks

The authors thank the discusser for his attention and discussion of our work. The comparison of dam damage under non-, single- and multi-pulse ground motions should be trustworthy since the numerical model presented in the original paper is able to capture the actual damage observed on the site. Hence, while the original paper may not use the very detailed numerical model for the dam, the used model is sufficient to support the comparative result that the multipulse ground motions are prone to cause more severe damage to dam compared to non- and single-pulse ground motions. Combined the results from the other two cases (i.e., frame structures and a soil slope), the conclusion in the original work that multipulse ground motions potentially require increased seismic demands than non- and single-pulse ground motions is also reliable.

Finally, the authors would like to reiterate the sentence from our original paper: 'This study recognizes that multipulse ground motions require significant seismic demands on structures, but more work is needed to comprehensively understand all important aspects of this issue.' This additional work includes employing more complex numerical models, enhancing the characterization of multipulse ground motions, implementing probabilistic seismic demand models, and integrating the seismology attributes. These investigations are of practical significance, and should be carried out once sufficient multipulse records become available.

Conflict of interest

The authors declare no potential conflict of interests.

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