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Assessment of sliding block methods performance considering energy-representative parameters

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ABSTRACT

In this research, permanent deformation of ten real earth dams were estimated using all the sliding block models and then, the errors between calculated deformations by each model and observed deformations of earth dams were presented and discussed in detail. The applied motion for estimating displacement of each dam was the recorded acceleration in the dam site. It was indicated that, conservative and non-conservative estimations of each model can be separated by Specific Energy Density and Response Ratio parameters in the time and frequency domains, respectively. It was also shown that, there is a logical relationship between the occurred earthquake-induced displacements and the specific energy density.

1. Introduction

Sliding block method, originally proposed by Newmark [1], for the prediction of the earthquake-induced permanent deformation of earthen structures has been implemented by many researchers during last five decades (e.g [2–4]). Three major approaches of Rigid, Decoupled and Coupled have been considered using Newmark sliding block model. Advantages and disadvantages of each approach and related derived models as well as progressive development of the approaches from Rigid to Coupled have been discussed by previous studies in detail (e.g [5,6]). However, after it was proved that Near-Field ground motions were capable of causing much higher level of damage for a wide range of earthen structures, only a few researchers considered the Near-Field concept, using sliding block models.

More recently, Garini and Gazetas [7] focused on near-field issue and discussed the sequence of high-duration pulses importance. Afterward, Voyagaki et al. [8] studied the sliding block system by applying near-field normalized pulses. They concluded that for constant values of PGA and material shear strength, existence of half-cycle pulse in velocity time history, may result in larger permanent deformation compared to full-cycle pulse. This conclusion contradicted the common understanding (e.g. [9,10]) of increase in permanent deformation due to increase in the number of shaking record cycles. Later, Gazetas et al. [11], by analyzing a number of near-field records containing forward directivity and fling step effects, indicated that the slip nature of sliding block may be affected not only by PGV and dominant period of the pulse, but also by some other unpredictable parameters such as pulse sequence details and polarity of the velocity pulse. Their study also revealed that the vertical component of the applied strong motion did not have significant effect on the sliding systems even when it had a large values of PGV in its velocity time history. It is worth noting that some of these finding had been mentioned by previous researchers such as Franklin and Chang [12]; Yegian et al.[10]; and Kramer and Lindwall [13]. Following previous studies, considering various parameters of a record containing forward directivity and/or fling step effects, Garini and Gazetas [14,15] indicated that the damage potential of the near-field strong motion records may be much greater than what was previously considered. So, they defined an upper bound for permanent deformation of sliding systems under near-field ground motions using rigid approach. However, while the accuracy of this method has not been examined using real case studies, it is consistent with the study performed by Rodriguez-Marek and Song [16] which expressed that the earthquake-induced deformations of earthen structures increased when they experienced a pulse-like forward directivity motion compared with experiencing a non-pulse motions.

In the present study, the calculated deformation of ten earth dams obtained by various approaches of Newmark method, are discussed in detail. These case studies included a total of 10 real dams which each of them experienced an earthquake with a reported measured displacement, with recorded motions at the dam site and with known characteristics. The selected cases were such that, they received a vast range of energy, without having significant changes in their motion frequency content due to the wave travelling. In other words, all the selected cases were located in near-field regions during the related earthquakes, while

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only some of them had experienced pulse like motions at their site. The applied motion for estimating displacement of each dam was the recorded acceleration at the dam site. Also, all the required parameters including yield acceleration, strong motion parameters such as PGA, PGV and Intensity, Initial fundamental period (Ts), earthquake Magnitude and Distance, and other parameters such as Sa(1.5Ts) were available or calculated. In other words, permanent deformations of the selected cases (10 earth dams) were estimated by 32 values of 26 models, derived from the five approaches of Rigid, Decoupled, Coupled, Unified and Near-Field. The predicted values were compared with the recorded slippage of the cases to determine conservatism and non-conservatism predictions of each model in both time and frequency domains. Consequently, the Specific Energy Density (SED) as a separator parameter in the time domain and the Response Ratio as a separator parameter in the frequency domain are introduced. Furthermore, it is proved that, SED may act as a major displacement predictive parameter as well as the other fundamental parameters such as yield coefficient (Ky) and initial fundamental period (Ts).

2. Case studies (10 Earth Dams)

The selected case studies, presented in Table 1, were located up to 15 km from the related fault and were shaken with an earthquake of Mw > 5.8. In addition, none of them have experienced liquefaction or failure phenomenon during the related earthquake and hence, all the deformations which were recorded during and after the earthquakes were earthquake-induced deformations. Also, all the properties of these 10 dams such as recorded strong motion, material properties, geometry and etc. were available. In other words, their deformations can be predicted using all the rigorous and simplified models. For these cases, the required parameters for the deformation analysis such as yield acceleration, ground motion parameters and etc., were obtained in this study using the same method.

The details of the studied earth dams are presented in Table 1.

As mentioned above, the strong motions used for estimating displacements of these earth dams, were the recorded motion at the dam site during related earthquake which are presented in Table 2. It is needed to mention that, for the cases with an intermediate depth or shallow sliding wedge, the input motions for Newmark analysis were obtained at the base of sliding blocks by performing numerical analysis.

Furthermore, it should be mentioned that, the recorded motion at the south-west abutment station of Coyote Lake dam was used to analyze this dam during Morgan Hill 1984 earthquake with special considerations [20] regarding the recorded motion scaling. Also, the strong motion used for analyzing Whittier Narrows dam was the recorded strong motion at the crest of the dam. However, both above mentioned records were scaled to an associated target response spectrum which were obtained from the attenuation relationship developed by Ambraseys and Douglas [21] for Near-Field Regions (R < 15 kM, M > 5.8), considering each site features during related earthquake.

For selecting an appropriate scaling method for Whittier Narrows dam, the following steps were taken:

1. Scaling the mentioned main recorded motion using following five different approaches:

 – scaling the motion to the target PGA
 – scaling the motion to fit the target response spectrum
 – matching the motion to fit the target response spectrum
 – matching the motion to fit the target response spectrum and the target PGV
 – scaling the motion to fit the target response spectrum at the site period

2. Applying the scaled motions as the input motion at the base of the dam via a numerical model
3. Calculating the motions at the crest of the dam, using the scaled motions as the input motions at the base of the dam
4. A comparison between calculated motions at the crest of the dam and the recorded real motion during the earthquake, in terms of Peak Crest Acceleration (PCA), Peak Crest Velocity (PCV) and response spectrum parameters such as Peak Spectrum acceleration (PSA) and Mean Shaking Period (Tm). These values are shown in Table 3.
5. Selecting the appropriate scaling method which produced the closest calculated motion to the recorded motion. As it is obvious in Table 3, the values related to the scaled motion to fit the target response spectrum are in good agreement with the values related to the real recorded motion.

The selected scaling method for scaling the main record of Whittier Narrows dam was also used for scaling the main record of Coyote Lake Dam. It is worth noting that the best scaling method due to results of this study (Table 3) was the method which scaled the motion to fit the target response spectrum. As mentioned previously, the target response spectrum were obtained from attenuation relationship developed by Ambraseys & Douglas [21] for Near-Field Regions (R < 15 kM, M > 5.8).

However, another evidence for the selected scaling method to be appropriate is that, the calculated max settlements by numerical models of the two dams using mentioned scaled records were in good agreement with the observed settlements via earthquake for these two dams. The calculated settlements for Whittier Narrows dam was 3 mm and for Coyote Lake dam was 73 mm which were in good agreement with the observed settlement of < 5 mm and 67 mm for these two dams, respectively.

3. Discussion of fundamental concepts

3.1. Newmark family models

In this research, a total of 32 predicted displacement values can be resulted from all 26 (rigorous and simplified) Newmark models within five approaches, which are categorized and introduced in Table 4.

Some important expressions mentioned in Table 4, are defined as below:

– Rigorous Analysis: Rigorous analysis calculates displacements using real ground motions.
– Simplified Analysis: Simplified analysis calculates displacements using parameters related to the associated ground motion.
– Simplified models: Simplified models usually can be developed utilizing rigorous analysis with special technics and considerations. They eliminate the need to use real ground motions.
– Rigid Approach: Rigid Block approach, first developed by Newmark [1], treats a potential landslide block as a rigid mass (no internal deformation) that slides in a perfectly plastic manner on an inclined plane.
– Near-Field Approach: This is a new approach derived from rigid approach. Analyzing near-field strong motion utilizing rigid method, led to a simplified possible upper bound for cases located in near-field regions [14].
– Decoupled Approach: Decoupled approach is a modification of traditional Newmark Rigid approach that does not require the potential landslide mass to behave as a rigid block but rather models its dynamic response. Decoupled sliding block analysis originally computes the dynamic response of sliding mass without considering changes due to sliding and then, uses the computed response in a Rigid-block analysis.
– Unified Approach: Actually, this approach is based on decoupled equivalent linear analysis of layered systems. However, in this approach, the initial values of displacements are calculated using rigid