Reliability of Simplified Newmark-Type Methods in Performance-based Seismic Design of Embankments

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ABSTRACT
The simplified Newmark-Type methods are recommended in many technical guidelines for evaluation of the seismic induced deformations and as a screening tool for performance-based seismic design of embankments. These methods are mostly known as a systematic approach to identify embankments with marginal factor of safety, assuming that they are always able to provide conservative estimates of displacements. Recent studies, however, have demonstrated that application of the simplified Newmark-type methods may not be conservative in some cases, especially when the tuning ratio of a dam is within a certain range. In this paper, the reliability of the simplified methods is examined based on the existing thresholds proposed in the literature for tuning ratio, considering the geometry and type of embankment and the seismic activity characterization. A practical framework for assessing the reliability of simplified Newmark-type methods is described and its effectiveness is evaluated in the study of seismic behavior of Zipingpu Dam where none of the simplified methods was able to predict the order of deformation experienced by the dam under a recent earthquake event.

1 INTRODUCTION

In the design of a new dam, or in evaluating the seismic performance of an existing dam, it is imperative to evaluate the potential deformations of the dam due to earthquake loading. The magnitude of the crest settlement of a dam must be less than the free board of the dam to prevent overtopping and breach. The guidelines on performance-based design of embankments have proposed different approaches for evaluation of earth dams under earthquake loading, ranging from simplified Newmark-Type procedures to complex stress-deformation analyses. Among these approaches, the simplified Newmark-Type methods are more popular in practice due to their simplicity and inexpensive application. However, recent studies show that these methods do not always give a conservative estimate of deformation of dams under earthquake loading (e.g. Rathje and Bray 2000, Wartman et al. 2003, Nejad et al. 2010, Meehan and Vahedifard 2013).

There are few proposed thresholds in the literature for the range of applicability of the Newmark-Type methods; e.g., Kan et al. (2017) proposed a framework to convert these thresholds to measurable practical engineering parameters related to the height and type of the embankment, and the seismic activity of the site. This framework and its application is further reviewed in the present paper from performance-based design perspective. The effectiveness of the proposed framework is also evaluated using a recent case history of earthquake effects on Zipingpu Dam, a well-compacted modern rockfill dam which suffered large deformations during 2008 Wenchuan Earthquake in China.

2 NEWMARK-TYPE SIMPLIFIED METHODS

Newmark (1965) proposed a method for evaluation of deformation of embankments due to earthquake loading, which became the basis for further theoretical research in this field. Newmark assumed that the behavior of a potential sliding mass in an embankment is similar to the behavior of a sliding block on an inclined surface. The block slides only if the earthquake acceleration becomes larger than the yield acceleration of the block. The yield acceleration of a potential sliding block (k_y) is a horizontal acceleration which results in yielding (or failure) along a slip surface with irrecoverable deformation and can be evaluated from a limit equilibrium analysis. The displacement of a block under earthquake loading can be calculated by double integration of the earthquake acceleration exceeding the yield acceleration of the block. The original Newmark method is often referred to as the “rigid sliding block” method.

Makdisi and Seed (1978) modified and improved the original Newmark method by considering the effect of deformability of embankment dams during earthquake loading. This contribution was based on two-dimensional finite element analyses of some real and hypothetical dams with heights ranging from 30 m to 60 m, constructed of compacted cohesive or stiff cohesionless materials. The analyses were based on the assumptions that the stiffness of the material is non-linear and is dependent on the level of the cyclic shear strain induced by earthquake loading. The magnitudes of the earthquakes considered range from 6.5 to 8.25. Different approaches have been derived from the Makdisi and Seed method. The more popular approach treats the slope as a deformable media and calculates the time history of acceleration of any failure mass along the slope of the dam accordingly. The deformation of the embankment can then be calculated based on the Newmark method. This approach is called “decoupled approach” after Kramer and Smith (1997).

3 RELIABILITY OF THE SIMPLIFIED METHODS

The original Newmark (1965) method and the one modified by Makdisi and Seed (1978) have been perceived to give conservative estimates of deformation of embankment dams under earthquake loading. These methods therefore are widely used as screening tools to identify dams with marginal safety. In most of the practical cases, more accurate methods such as stress–deformation analysis are considered, only if the crest settlement obtained by these methods is larger than (or close to) the free board of a dam (e.g. USBR, 1989).

The results of some recent studies however show that simplified Newmark-type methods may not always be conservative. Rathje and Bray (1999, 2000) and Wartman et al. (2003) have found that the tuning ratio (ratio of the fundamental period of a dam to the mean or predominant period of earthquake) has an important effect on the deformation of earth structures due to earthquake loading and the simplified procedures may be non-conservative within a certain range of tuning ratios. A summary of these investigations is presented in Table 1. It should be noted that the critical thresholds are mainly introduced based on k_y/k_{max} (ratio of the yield acceleration to the maximum induced acceleration) and the tuning ratio, T_o/T_m. It can be seen that although there is no well-defined boundary where the simplified method clearly becomes non-conservative, a tuning ratio of greater than one can be regarded as a “critical threshold” beyond which the performance of the simplified Newmark-type methods, such as Makdisi and Seed (1978), may become unreliable and potentially non-conservative.

Some numerical studies also suggest that the simplified methods do not always give a conservative estimate of deformation (e.g. Ghanooni and MahinRoosta, 2002, Feizi-Khankandi et al., 2009, Nejad et al., 2010 & 2011, Sengupta, 2010). Strenk and Wartman (2011) performed a series of probabilistic analyses to evaluate the permanent deformations predicted by the rigid block and decoupled methods. They concluded that the widely accepted notion that these methods could give the crest displacement with accuracy within one order of magnitude may become misleading.

Meehan and Vahedifard (2013) compared the predictions of fifteen Newmark-type simplified methods with the displacements records of 122 earth dams and embankments under seismic loading and showed that the results of the simplified methods are not always conservative. The displacements predicted by some of the methods were less than the observed deformations, with differences as high as 1 m for few cases.

Table 1. Theoretical studies on simplified methods.

Reference	Rigid Block Analysis	Decoupled Analysis (e.g. Makdisi and Seed,1978)
Rathje and Bray (1999)	Non-conservative for $0.2<T_o/T_m<2\sim3$	Conservative for $T_o/T_m<2$ and $k_y/k_{max}<0.6$ Non-conservative for $T_o/T_m>4$
Rathje and Bray (2000)	Might be significantly non-conservative or highly conservative	Conservative for $T_o/T_m<1$ May be non-conservative for $T_o/T_m>1$ Potentially non-conservative for large T_o/T_m, and $k_y/k_{max}>0.4$ Primarily non-conservative for large T_o/T_m, low k_y and intense ground motion
Wartman et al. (2003)	Non-conservative for $0.2\leq T_o/T_m\leq 1.3$	-

4 A FRAMEWORK TO VERIFY THE RELIABILITY OF THE SIMPLIFIED METHODS

Kan et al. (2017) introduced a framework to assess the reliability of simplified Newmark-type methods in seismic performance-based design of embankments. They proposed a systematic approach to convert the previously introduced critical thresholds of the tuning ratio into measurable practical engineering parameters related to the height and type of the embankment, and the seismic activity of the site. A brief review of this framework is presented in this section.

The most important advantage of the simplified methods in deformation analysis under earthquake loading is their simplicity and cost-effectiveness so that they can easily be used as screening tools. Therefore, it is important to know when such a procedure could be relied upon in a systematic engineering design.

Based on the results of recent investigations and the discussions, Kan et al. (2017) assumed that the critical threshold of the tuning ratio beyond which the simplified Newmark-type methods may not be conservative is: $T_o/T_m > 1$. They presented a procedure through which the tuning ratios for different earthquakes and different dam heights and types can be approximated.

In evaluating the tuning ratio of dams under different earthquake motions, the mean period of the earthquakes, T_m, should be evaluated. Rathje et al. (1998) used the records of 306 stations from 20 strong earthquakes in regions of active plate-margin of the western United States and developed an empirical relationship that defines the magnitude, distance, and site dependency of the frequency content for different earthquakes. They also proposed a relationship for evaluation of the mean period of earthquakes for shallow crustal earthquakes in stable continental regions (e.g., the eastern United States and Australia). For a dam within 100 km of a causative fault, which is common in regions with medium to high seismic potentials, the mean period of ground motions for different earthquake magnitudes would be in the range of 0.45 s to

0.8 s for regions around active plate margins, and between 0.21 s and 0.45 s for stable continental regions.

Singh and Roy (2009) gathered data on the performances of 152 dams, which were subject to deformation during earthquakes. The recorded period of the earthquakes versus distance to epicentre is shown in Figure 1. It shows that around 88 percent of these earthquakes occurred within 100 km from the dams with mean periods ranging from 0.25 s to 0.7 s.

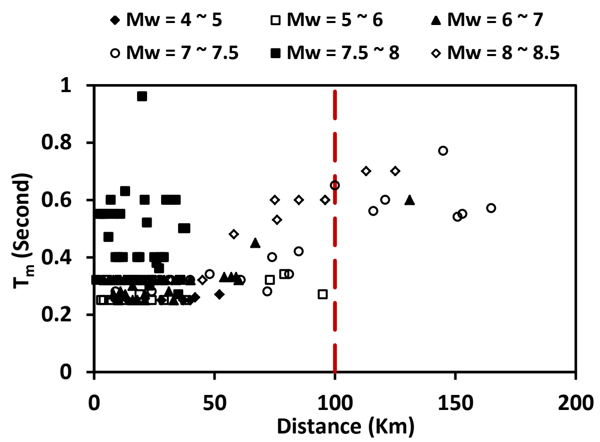

Figure 1. Variation of the period of earthquakes versus distance in 152 dams (data from Singh and Roy, 2009).

Kan et al. (2017) considered the minimum value of the mean period (T_m) of the ground motions within the possible range, with setting the critical threshold of $T_o/T_m = 1$. They concluded that if the fundamental period of a dam is greater than 0.45 s in regions of active plate margins and 0.21 s in stable continental regions, the decoupled approach of Makdisi and Seed might become unreliable.

On the other hand, the fundamental period of a dam can be approximately related to its height and material properties. For a given homogenous triangular shaped earth/rockfill dam with height of H, Hatanaka (1955) showed that the fundamental period can be derived from:

$$T_o = 2.61\frac{H}{V_s} \quad [1]$$

where H is the height of the dam and V_s is the shear wave velocity of the dam material. V_s could be expressed as a function of the shear modulus, G, and mass density, ρ, of the material:

$$V_s = \sqrt{\frac{G}{\rho}} \quad [2]$$

Gazetas (1987) proposed an equation for variation of shear modulus along the height of a dam:

$$G = G_b(\frac{z}{H})^m \quad [3]$$

where G_b is the average shear modulus at the base of the dam and z is zero at dam crest, increasing to H at the base. The value of m varies between 0.3 and 0.8. The value of $(\frac{z}{H})^m$ for a representative point within $(\frac{z}{H})$ of 0.5 to 0.67 (between the mid-height and centroid of the dam section) has a mean value of around 0.7. Therefore, the average shear modulus can be approximated as:

$$G_{avg} \approx 0.7\ G_b \quad [4]$$

where G_b can be taken equal to G_{max} of Seed and Idriss (1970), based on the following relationship for the shear modulus of granular material:

$$G_b = 220(K_{2\max})_{avg}\ (\sigma_o)^{0.5} \quad [5]$$

where σ_o is the average mean effective stress at the base of the dam. K_{2max} ranges from 80 to 180 for gravels (Kramer, 1996) and 52 to 70 for sands (Seed and Idriss, 1970). $(K_{2max})_{avg}$ represents the mean value of K_{2max} for different materials used in the dam. Therefore, the fundamental period of a dam, T_o could be calculated as a function of H, γ ,and $(K_{2max})_{avg}$. The value of unit weight, γ (in kN/m^3), and coefficient of lateral pressure, K_o, can be well approximated within the narrow range appropriate for dam materials and therefore, T_o simply becomes a function of dam height (H, in meters) and $(K_{2max})_{avg}$. The accuracy of such simple function for T_o mainly relies on the underpinning simplified theories and field observations as highlighted in derivation, though all approximations are widely accepted in practice.

Figure 2 and Figure 3 show the variation of T_o as a function of H for two different ranges of $(K_{2max})_{avg}$: the range 50 to 80 which is more suitable for earthfill dams and the range 90 to 170 which is suitable for well- compacted rockfill dams. The values of γ and K_o in these figures are assumed 20 kN/m^3 and 0.5, respectively.

Recalling the critical range of T_o (0.45 s or 0.21 s), the critical height of dams where the decoupled approach is potentially non-conservative can be obtained from these two figures. In general it can be concluded that in the active seismic regions (e.g. western U.S. and China) the critical height for earthfill dams is between 50 m and 65 m and for rockfill dams is between 75 m and 110 m. Similarly, in the stable continental regions (e.g. Australia) the critical heights are between 20 m and 30 m for earthfill dams and between 30 m and 45 m for rockfill dams. Note that in the development of Makdisi and Seed's method, the maximum dam height was limited to 60 m and therefore the effects of tuning ratio, for earthquakes in the active seismic regions of US, could not be detected by the method.

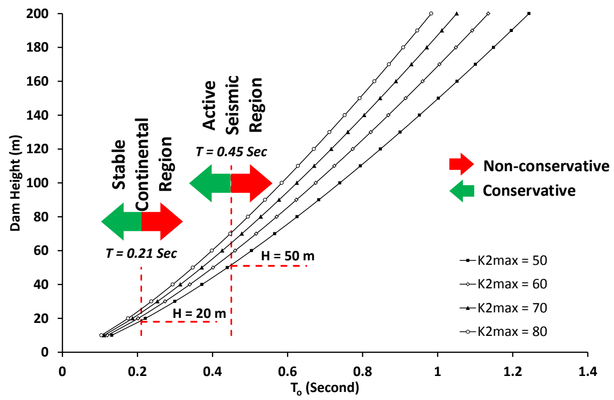

Figure 2. Variation of fundamental period with height for earthfill dams.

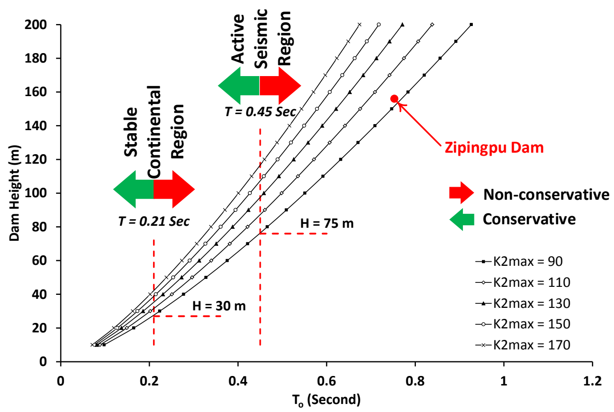

Figure 3. Variation of fundamental period with height for rockfill dams.

5 APPLICATION OF THE FRAMEWORK IN A CASE STUDY

In this section the observed deformations of a large concrete faced rockfill dam are compared with the results of deformation analyses using the Newmark rigid block method and the Makdisi and Seed decoupled method. It is intended to evaluate the performance of the above mentioned framework.

Zipingpu dam is one of the largest modern concrete face rockfill dams in the world. The '5.12' Wenchuan Earthquake hit this dam severely in May 2008 and caused relatively large permanent displacements to the dam (Kong et al. 2010). A cross section of the dam at its deepest point is shown in Figure 4. The maximum height of the dam is 156 m, with a 664 m long 12 m wide crest. The upstream slope of the dam is 1V:1.4H. Two downstream berms at EL. 796.0 and 840.0 m with a width of 6 m provide an average downstream slope of 1V:1.5H (Xu et al., 2012). The '5.12' Wenchuan Earthquake had a moment magnitude of about M_w 8 and caused a maximum permanent settlement of 1 m and a horizontal displacement of 0.6 m to the dam crest (Chen and Han, 2009). The time history of the earthquake acceleration as shown in Figure 5 is used as the base ground motion for the dam. The record is a bedrock acceleration time history recorded 75 km from the Zipingpu dam and scaled to attain a PGA of 0.55g, following Zou et al. (2013). This is an 80 seconds long record with high frequency content and an extremely low predominant period of 0.12 seconds.

To calculate the deformation of the dam using the Makdisi and Seed decoupled method, four sliding blocks on the downstream side of the dam were taken into account, ranging from 1/6 to 1/1 of the dam height. In order to calculate the yield acceleration for each sliding block, pseudo-static analyses were performed. The unit weight of the rockfill material was taken as 21.6 kN/m^3, the peak friction angle of the rockfill was assumed to be 45° and a nominal cohesion of 15 kPa was considered to prevent failure of very shallow sliding blocks in the analyses. The pseudo-static analyses were performed using Spencer's method in Slope/W (Geo-Slope International Ltd., 2007). The horizontal yield acceleration, which brings a block to the onset of failure (Factor of Safety = 1), was found by a trial and error approach.

To calculate the induced acceleration on each sliding block due to the earthquake, a simple stress–deformation analysis was performed on the dam in FLAC 2D (Itasca Consulting Group Inc. 2008), utilizing an equivalent linear constitutive model for the rockfill material (Kan and Taiebat, 2015). The elastic shear modulus was evaluated from the equation proposed by Kokusho and Esashi (1981) for coarse gravels:

$$G_{max} = \frac{13000(2.17-e)^2}{1+e}(\sigma_o)^{0.55} \qquad [6]$$

where G_{max} is the small strain shear modulus, σ_o is the mean effective stress and e is the void ratio. Values of G_{max} were calculated for each element using the actual value of σ_o and e evaluated after the reservoir impoundment. The small strain bulk modulus is also calculated using the theory of elasticity assuming a Poisson's ratio of 0.3 for rockfill materials. These small strain elastic parameters are subjected to degradation at higher shear strains when the material undergoes cyclic loading. The degradation function is assumed to follow the upper-bound curve proposed by Seed and Idriss (1970) for granular materials.

The average induced acceleration on a block at any time is calculated as the weighted average of the accelerations of all grid points inside the block obtained by the equivalent linear model. For example, the average induced acceleration calculated for shallowest block (1/6 height of the dam) is shown in Figure 6. The time history of the maximum permanent displacement of sliding blocks is also shown in Figure 7, showing a maximum displacement of 0.14 m which is clearly much less than that observed in the field.

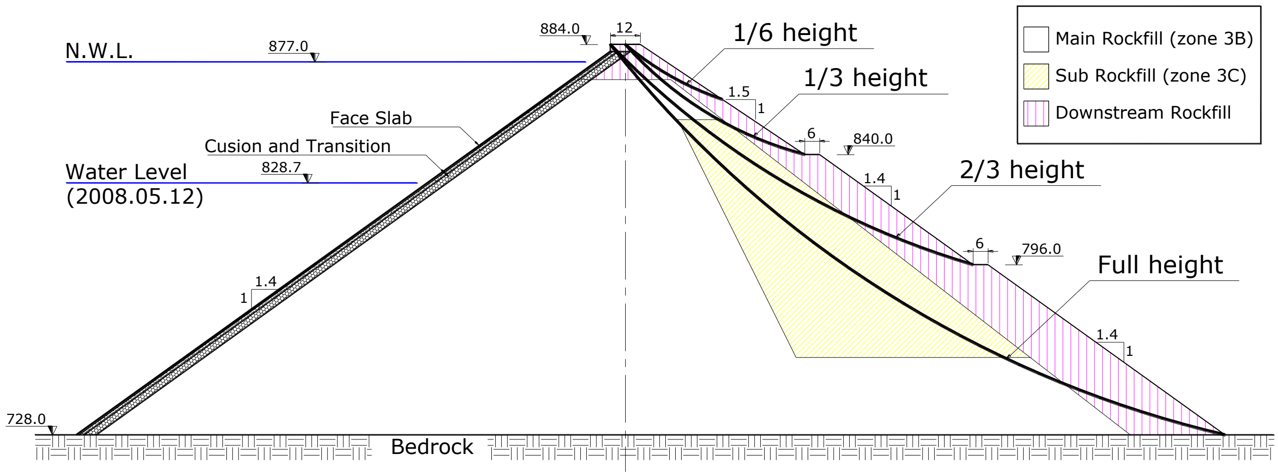

Figure 4. Deepest cross section of Zipingpu dam (cross section 0+251, all units in Meters) and location of slip surfaces.

Many analytical models have been proposed based on the Newmark sliding block concept in order to simplify the application of the method using a single equation. It is of interest to study the performance of these models in predicting the behaviour of Zipingpu dam. All these models are used to predict the displacement of Zipingpu dam under the earthquake loading. The predicted displacements obtained from these models are listed in the last column of Table 2 and shown graphically in Figure 8, where all displacements are consistently projected along the slope batters of the dam. It can be seen that the displacements predicted by most of these models are less than the observed displacement, with the exception of Bray and Travasarou (2007) model which over-predicts the displacement by 60%.

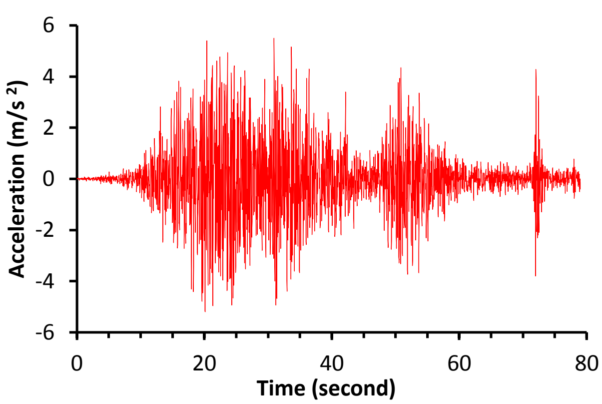

Figure 5. Acceleration time history of the "5.12" earthquake (scaled to 0.55g).

The reliability of the simplified Newmark-type methods in calculating the deformation of Zipingpu dam can be evaluated according to the guideline presented in current study. The fundamental period of the dam is calculated as 0.753 s using the procedure outlined in Makdisi and Seed (1979). The mean period of the Wenchuan Earthquake is 0.21 second. Therefore, the tuning ratio (T_o/T_m) of the system is around 3.6, which is much higher than the critical threshold of 1. Figure 3 also shows that the fundamental period and height of the Zipingpu dam is on the range where application of the simplified methods is non-conservative for active seismic regions.

Table 2. Different simplified models and their prediction of displacements of Zipingpu dam.

Reference	Main application	Predicted displacement (cm)
Franklin and Chang (977)	Earth embankments	4.0
Makdisi and Seed (1978)	Earth dams and embankments	14.1
Richards and Elms (1979)	Gravity structures	3.9
Hynes-Griffin and Franklin (1984)	Earth dams	0.7
Ambraseys and Menu (1988)	Ground and slopes	3.3
Yegian et al. (1991)	Earth dams and embankments	47.7
Bray et al. (1998)	Landfill slopes	9.3
Watson-Lamprey and Abrahamson (2006)	Earth slopes	1.8
Bray and Travasarou (2007)	Earth and waste slopes	161.3
Jibson (2007)	Natural slopes with 4 different methods	3.3
		8.7
		0.04
		9.6
Saygili and Rathje (2008)	Natural slopes	3.7
Rathje and Antonakos (2011)	Natural slopes	0.5

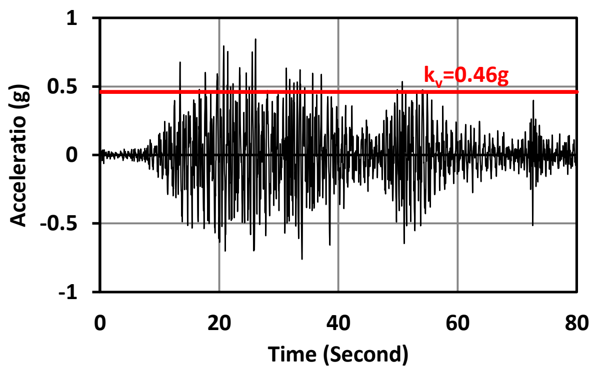

Figure 6. Acceleration time history for the shallowest sliding block in Zipingpu dam.

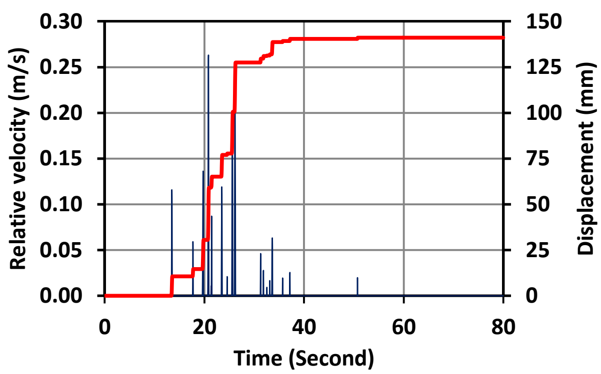

Figure 7. Records of relative velocity (blue) and permanent displacement (red) of the shallowest sliding block.

6 SUMMARY AND CONCLUSIONS

The simplified Newmark-type methods are widely used in practice to evaluate the deformation of embankment dams under earthquake loading. These methods are relatively simple and inexpensive in comparison with the complicated numerical methods. They are also recommended by some codes and guidelines to be used as a screening tool to identify cases with marginal safety for which a more accurate method could be utilised. This is acceptable only if it is assumed that these methods can systematically give conservative estimates of crest deformations. Nevertheless, recent stress–deformation analyses and theoretical investigations show cases where these methods are not conservative, as were assumed before.

Based on theoretical and experimental studies, it is concluded that the simplified methods are potentially non-conservative when the tuning ratio (T_o/T_m) is greater than the critical threshold of 1.0. Based on this assumption, a set of charts is presented, for different types of dams and different seismic regions, which define the range of height-to-fundamental period of dams for which the simplified methods are reliable and conservative. These charts show that the simplified method of Makdisi and Seed (1978) is potentially non-conservative for embankment dams higher than 50 m in the active seismic regions and higher than 20 m in the stable seismic regions.

The reliability of simplified Newmark-type methods in predicting the deformation of the Zipingpu dam was also discussed. It is shown that the decoupled approach gives a crest displacement much less than those observed in the field. The majority of other models proposed based on the concept of the Newmark sliding block also fail to predict a conservative displacement for the Zipingpu dam. This can be attributed to the nature of the input motion which has a very high frequency, rendering a tuning ratio much higher than 1.0.

It should be noted that the critical threshold of the tuning ratio selected in this study is based on previous investigations which were mainly focused on natural slopes and landfills. Therefore it would be necessary to study the effects of the tuning ratio on seismic performance of dams more specifically and to be able to evaluate the critical threshold for dams more accurately.

The proposed framework to assess the reliability of Newmark-type methods for evaluation of seismic-induced displacement of the embankments is a general approach in concept, based on the characteristics of the input seismic motion (depicted in T_m) and geometry and material type of the dam (represented by T_o). However, application of the derived critical dam heights for design of embankments in active seismic regions and stable continental regions shall be considered within the limitations of the underpinning data and simplifications in calculation of the fundamental period of the dam.

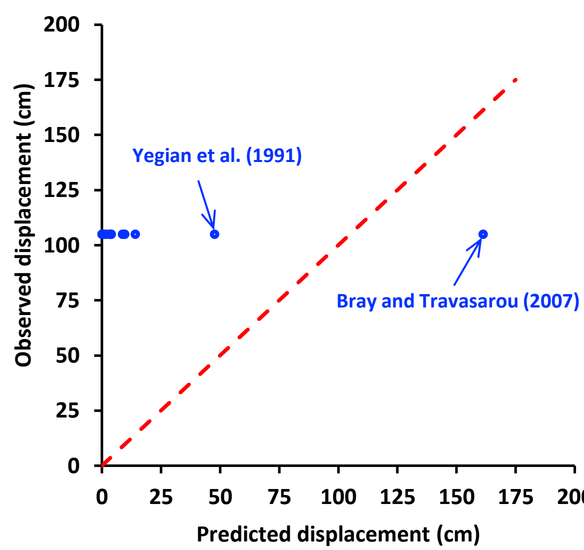

Figure 8. Observed vs. predicted displacements of Zipingpu dam obtained from simplified models.

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