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Evaluation of simplified methods for predicting earthquake-induced slope displacements in earth dams and embankments

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ABSTRACT

This paper provides a review and comparison of existing simplified displacement-based sliding block models. Analyses were performed to evaluate the relative accuracy of fifteen of these simplified models for predicting earthquake-induced displacements. To accomplish this task, the predictive capability of the models was assessed by comparing model predictions with the actual displacements that were observed after earthquake shaking in 122 case histories of earth dams and embankments. The results indicate that the model predictions of displacement were less than the observed displacement for a large majority of the case histories that were examined. The difference between the observed and predicted displacements was relatively large for a significant percentage of the cases, for each model that was examined. The shapes and positions of the models' relative error cumulative distribution functions did not change significantly if the case histories were filtered to include only those with intermediate levels of observed displacement (i.e., 0.01 m<observed displacement<1 m), which indicates that the simplified models may exhibit the same behavior for cases of small and/or large displacements as they do for cases in the intermediate range, provided that a percentage-based approach such as relative error is used to compare the results from different models.

1. Introduction

Earthquakes pose a significant threat to a wide range of geotechnical projects, including those that involve natural slopes, earth dams, solid-waste landfills, retaining walls, tunnels, or foundations. To minimize earthquake-induced losses in these structures, two essential questions have to be considered: first, will earthquake shaking significantly decrease the strength of any material in the structure or its foundation (e.g., liquefaction, strain-softening)? If a significant loss of soil strength occurs, there is a strong possibility of catastrophic structural failure, either during the earthquake itself or after completion of earthquake shaking (Bray, 2007). If significant strength loss does not occur, the second question that follows is: will an earthquake impose significant permanent deformations to a structure such that its post-earthquake performance is endangered (Bray, 2007)?

For those cases where significant strength loss does not occur, a variety of techniques have historically been used to evaluate seismic slope stability. These techniques typically fall into one of the following categories, in order from low to high complexity: force based pseudo-static methods, displacement-based methods (sometimes referred as Newmark-type or sliding block methods), and stress-deformation analyses through numerical methods, such as finite element or discrete element methods (Kramer and Smith, 1997). As an intermediately complicated and accurate approach, displacement-based methods developed based on sliding block theory produce a reliable index of slope performance under seismic loading through their predictive calculation of permanent earthquake-induced displacements (e.g., Kramer and Smith, 1997).

Since Newmark's (1965) introduction of the sliding block method, numerous displacement-based analytical methods have been proposed to improve upon the accuracy of Newmark's original method (e.g., Makdisi and Seed, 1978; Kramer and Smith, 1997; Rathje and Bray, 2000), to simplify its use (e.g., Franklin and Chang, 1977; Ambraseys and Menu, 1988; Jibson, 2007; Hsieh and Lee, 2011; Rathje and Antonakos, 2011), or to apply the general concept of the model to applications beyond those originally proposed by Newmark (e.g., Richards and Elms, 1979; Ling and Cheng, 1997; Ling et al., 1997). More recent studies have also been performed to characterize uncertainties associated with Newmark-type models (e.g., Strenk and Wartman, 2011). The number of displacement-based models that have been proposed is quite significant, and it is consequently difficult for practicing engineers to ascertain which model should be selected for application to a given problem. This paper will focus on design methods that have been developed to simplify the use of sliding block models, which will hereafter be referred to as *simplified*

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sliding block methods. It should be emphasized that, in some cases, the application of simplified sliding block models is not truly a "simple" task, as a large number of relatively sophisticated input parameters are sometimes required.

This paper seeks to perform two tasks: (1) to provide a thorough review of existing literature that summarizes and organizes a large number of simplified sliding block models, making these empirical equations more accessible for use by practicing engineers, and (2) to evaluate the relative accuracy of a number of existing simplified sliding block models for predicting earthquake-induced displacements. To accomplish the second task, the predictive capability of fifteen simplified sliding block models is assessed by comparing model predictions with the actual displacements that were observed after earthquake shaking in 122 case histories of earth dams and embankments.

2. Development and evolution of sliding block models

Newmark (1965) is often credited with the first development of a displacement-based "sliding block" method for the dynamic analysis of earth dams and embankments. As noted by Marcuson (1995), it is probably also appropriate to cite the early development of displacement-based approaches in seismic slope stability to contributions made by Whitman and Taylor (e.g., Taylor, 1953). Early pioneers in this area also include Goodman and Seed (1965), who used a similar displacement-based method instead of traditional pseudo-static analysis to evaluate slope performance under earthquake shaking.

Newmark (1965) assumed that the dominant mechanism for earthquake-induced displacement in dams involved sliding shear along a well-defined failure surface. He proposed that the dynamic behavior of a sliding mass could be simulated by modeling the mass as a rigid block sliding on an inclined base. Using this approach, a threshold acceleration is defined that corresponds to the inertial force that must be applied to overcome the shear resistance between the block and the base. In current practice, this acceleration is commonly referred to as the "critical" or "yield" acceleration, and it is usually assumed to be the inertial acceleration that yields a factor of safety of one in a pseudo-static analysis of the slope. Using Newmark's approach, sliding will commence when the shaking-induced acceleration exceeds the critical acceleration. The cumulative seismic displacements can be calculated by integration of everywhere the relative velocity of the sliding block is greater than zero.

In practice, values of critical acceleration are typically estimated using a trial and error approach in conjunction with conventional limit-equilibrium slope stability methods. Explicit equations have also been developed to directly estimate the critical acceleration for relatively uniform slopes and simple failure mechanisms (e.g., Bray et al., 1998; Jibson et al., 2000) or non-circular failure mechanisms (e.g., Sarma, 1973) as a function of critical input parameters such as slope geometry, the cohesion and friction angle of the soil, and the unit weight of the soil. For certain applications such as rigorous probabilistic analyses or landslide hazard mapping, relatively simple functional forms that can be used to determine critical acceleration can significantly decrease the required computational effort, and may be appropriate for use given the relative uncertainty of model input parameters.

Newmark's sliding block model was developed and is commonly implemented following a number of simplifying assumptions. A significant amount of research has been conducted to examine the sensitivity of predicted seismic displacements to these assumptions, and in many cases, new models or modifications to Newmark's original model have been proposed to improve the accuracy of the predicted displacements. The limiting assumptions associated with Newmark's original model and some of the pertinent studies that have been performed by others to study the effects of these assumptions are as follows: (a) the dynamic response of the failure mass does not affect the earthquake-induced displacement (e.g., Makdisi and Seed, 1978; Lin and Whitman, 1983; Hynes-Griffin and Franklin, 1984; Kramer and Smith, 1997; Bray and Rathje, 1998; Rathje and Bray, 2000; Wartman et al., 2003; Rathje and Antonakos, 2011); (b) the potential failure mass of the slope fails following a rigid-perfectly plastic type of failure mechanism (e.g., Kutter and James, 1989; Yan et al., 1996; Mendez et al., 2009); (c) the critical acceleration remains constant during shaking, corresponding to no increase or loss of strength due to earthquake shaking (e.g., Houston et al., 1987; Kutter and James, 1989; Matasovic et al., 1997); (d) permanent displacement occurs just in the downward direction, and "upslope sliding" does not occur (e.g., Yan, 1991; Matasovic et al., 1998); (e) the vertical component of the ground motion does not affect the earthquake-induced displacement (e.g., Yan et al., 1996; Ling and Leshchinsky, 1998; Kramer and Lindwall, 2004; Sawicki et al., 2007); (f) the displacements accumulate along a single, well defined failure surface (e.g., Kutter and James, 1989; Nguyen et al., 2005; Wartman and Strenk, 2006); (g) the soil shear rate doesn't influence the permanent displacement that occurs (e.g., Lemos and Coelho, 1991; Tika-Vassilikos et al., 1993); and (h) the effect of pore water pressure is ignored (e.g., Sarma, 1975; Kutter and James, 1989; Meehan et al., 2008).

In addition to the modifications proposed above, others have suggested extending the use of Newmark's method to earthquake engineering applications beyond earth dams and embankments. In some cases, it is necessary to modify the formulation or the framework of the model in order for this extension to be reasonable. Some of the more commonly encountered applications are as follows: conventional gravity retaining walls (e.g., Richards and Elms, 1979; Whitman and Liao, 1985), waste slopes and landfills (e.g., Kramer and Smith, 1997; Matasovic et al., 1997; Bray and Rathje, 1998), geosynthetic-reinforced slopes and mechanically stabilized earth walls (e.g., Ling et al., 1997; Paulsen and Kramer, 2004; Huang and Wu, 2006), anchor-reinforced slopes (e.g., Trandafir et al., 2009); rock slopes (e.g., Ling and Cheng, 1997); and earthquake-triggered landslides and hazard mapping (e.g., Wilson and Keefer, 1983; Jibson et al., 2000; Miles and Keefer, 2000; Saygili and Rathje, 2009).

3. Simplified sliding block methods

In order to predict earthquake-induced displacements using Newmark's method, it is necessary to have both an input acceleration time series that corresponds to the earthquake ground motion, and a critical acceleration which is representative of the dynamic shear resistance of the slope. As discussed in the previous section, numerous other analytical methods have been proposed using this framework, many of which also require determination of a site specific acceleration time history for input into the analysis. The determination of a site specific acceleration time history is commonly performed using a selection process that looks for sites that have been shaken by an earthquake of similar magnitude, that are located at a similar distance from the earthquake source, and that have similar ground conditions. In some cases, a number of acceleration time histories are used in conjunction with Newmark's method for a given site, and postulated acceleration records are scaled to achieve the desired level of shaking.

The selection of site specific ground motions and appropriate scaling factors is a rather complicated process that typically involves a certain level of expertise and judgment (e.g., Watson-Lamprey and Abrahamson, 2006). As a result, a number of *simplified sliding block methods* have been proposed that require only characteristic ground motion input parameters such as the peak ground acceleration (a_{max}), peak ground velocity (v_{max}), earthquake moment magnitude (M), Arias intensity (I_a), etc. in the place of acceleration time histories. In order to develop these methods, researchers typically have performed analytical sliding block analyses using a range of critical acceleration values in combination with a database of ground motions. Earthquake-induced displacements are predicted for each