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A general model for predicting the earthquake-induced displacements of shallow and deep slope failures

Chi-Chin Tsai *, Yu-Chun Chien

Department of Civil Engineering, National Chung Hsing University, Taiwan

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ABSTRACT

The accurate assessment of the stability of slopes during earthquakes has become a critical issue in seismically active areas. To readily evaluate seismic slope hazards in a region, we developed an empirical model for estimating seismic slope displacements for both shallow and deep types of failures (i.e., rigid and flexible sliding mass, respectively). The prediction model is simply a function of peak ground acceleration (PGA) and mean period of ground motions (T_m). For predicting displacement of shallow failure, the PGA and T_m of incident motion can be directly used in the model. For predicting the displacement of deep failure, however, the dynamic response of flexible sliding block interacts with the incident motion. The changed PGA and T_m, defined as k_{max} and $T_{m,k}$ for the seismic loading of flexible sliding mass, respectively, is estimated depending on the natural period of sliding mass (T_s). Therefore, the predicting displacement of flexible mass is achieved using k_{max} and $T_{m,k}$ in lieu of PGA and T_m in the developed rigid model. This general model provides a consistent approach for predicting the sliding displacement of shallow (rigid) and deep (flexible) slope failures.

1. Introduction

Earthquake-induced landslides often cause thousands of deaths and injuries, thus inducing huge economic losses. Keefer (1984) reported that landslides caused >50% of the economic losses in the great Alaska earthquake of 1964 [Magnitude (Mw) = 9.2]. The 1989 Loma Prieta, California earthquake (Mw = 6.9) generated landslides throughout an area of roughly 15,000 km^2 in central California (Keefer, 2000). During the 1999 Chi-Chi earthquake (Mw = 7.6), >10,000 landslides of various types were triggered in the steep mountainous terrain of Central Taiwan throughout an area of approximately 11,000 km^2 (Hung, 2000). The accurate assessment of the stability of natural slopes and earth structures during earthquakes has become a critical aspect of the safe and cost-effective design of several projects in seismically active areas.

The available methods for assessing the performance of slopes during earthquake shaking, according to the order from low to high complexity, include pseudo-static methods, displacement-based (Newmark-type) methods, and stress-deformation numerical methods (finite element or discrete element methods) (Jibson, 2011). As an intermediately complicated and accurate approach, a displacement-based method produces a reliable index of slope performance under seismic loading through the predictive calculation of permanent earthquake-induced displacements. The displacement-based methodology (Newmark, 1965), referred to as rigid-block analysis, is extensively used in engineering practice to estimate earthquake-induced displacement. Several prediction models (e.g., Jibson, 2007; Saygili and Rathje, 2008; Bray and Travasarou, 2007) have been developed to correlate ground motion parameters with permanent displacements based on rigid block analysis.

However, these models are only applicable for estimating shallow slope failure in which the sliding mass can be approximated as a rigid block. In this case, the brittle surficial material behaves rigidly, and the relatively thin landslide masses do not experience a significant site response that would modify the incident ground motions as shown in Fig. 1. For a deep slope failure, ground motions could be de-amplified at deep failure planes because of its interaction with the deformable sliding mass above. These interaction behaviors should be considered in estimating earthquake-induced displacement. Ideally, the dynamic response of the sliding mass and the permanent displacement should be modeled together (referred to as coupled analysis), such that the effect of plastic sliding displacement on the ground motions is taken into account. Coupled analysis is the most sophisticated form of sliding-block analysis but also the most computationally intensive. Therefore, decoupled analysis (Makdisi and Seed, 1978; Bray and Rathje, 1998) is typically used instead. A decoupled analysis estimates the effect of dynamic response on permanent sliding in a two-step procedure: (1) A dynamic-response analysis of the slope (1D or 2D) is performed to estimate the acceleration-time histories at several points within the potential failure surface slope. The acceleration, accounting for the flexibility/deformability of sliding block, is variously referred to as seismic coefficient k (Makdisi and Seed, 1978); peak values are generally denoted as k_{max}. (2) The resulting k-time history that reflects the dynamic response of deformable sliding block is input into a rigid block analysis, and the permanent displacement is estimated.

* Corresponding author.

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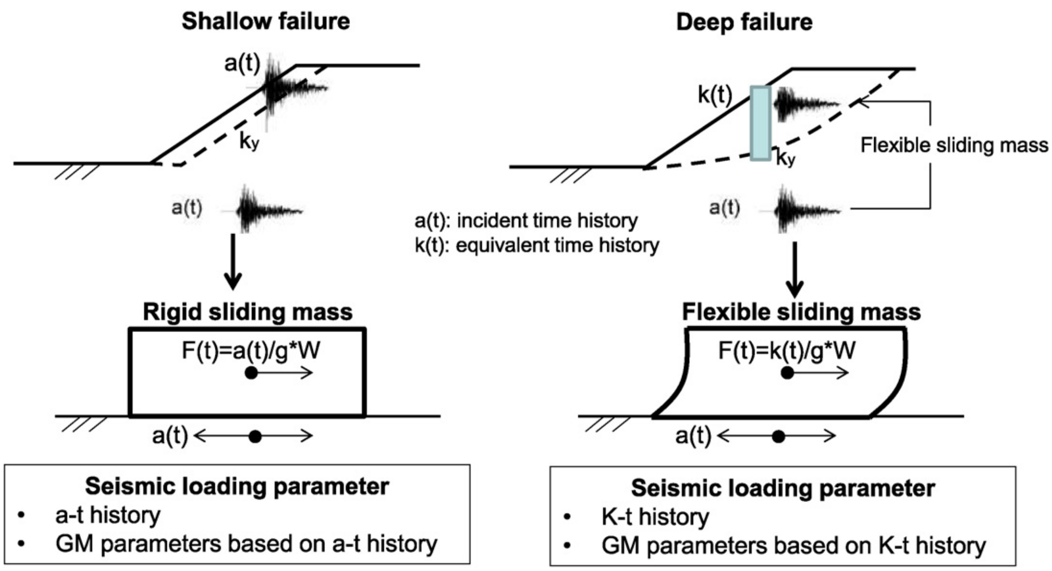

Fig. 1. Decoupled analysis to estimate displacement of flexible sliding mass.
After Rathje and Antonakos (2011).

According to the decoupled approach, Rathje and Antonakos (2011) proposed a hypothesis that the rigid block empirical models can be used under the condition of ground motion (GM) parameters replaced by those accounted for the amplification and deformability of sliding mass. Therefore, the relationship between GM parameters based on the equivalent acceleration-time history (k-time history) and those based on incident acceleration-time history was established. In their study, the changed GM parameters, such as peak ground acceleration (PGA) and peak ground velocity (PGV), are used in the rigid block model developed by Saygili and Rathje (2008) to predict the displacement of deformable block. However, using PGA and PGV as GM parameters is limited to the existing model, and may be incapable of fully capturing the change of incident wave, such as elongation of period. Consequently, the rigid model using altered GM parameters should still be corrected with additional parameters to accurately estimate displacement for flexible sliding mass.

In this study, we follow the same hypothesis by Rathje and Antonakos (2011) to develop a general prediction model for the displacement of rigid and flexible sliding mass. However, instead of using the existing rigid model in which the adopted GM parameters may be incapable of fully characterizing the k-time history, we develop a new (rigid) model at the beginning and consider the possible GM parameters based on their capability to characterize the k-time history in advance. In other words, the developed model is capable of predicting the displacement of rigid and flexible sliding mass. Key GM parameters dominating the displacement calculation are initially evaluated based on the model form suggested by Saygili and Rathje (2008). A new general model is subsequently developed, which considers the later application to flexible sliding mass. Moreover, the relationship between the GM parameters based on the k-time history and those based on the incident acceleration-time history is established. Therefore, the predicting displacement of flexible mass can be achieved using altered GM parameters in the developed general model.

2. Prediction equation for Ridge block sliding

2.1. GM parameters in a previous empirical model

Previous studies have proposed several simplified models to rapidly estimate earthquake-induced displacement. The GMs adopted in these models are the crucial aspects that dominate the displacement calculation. Kim and Sitar (2003) investigated the key factors that influence seismic slope displacements using simulated acceleration-time histories. They concluded that variability in calculated seismic displacement is primarily controlled by the significant variability in earthquake GM and is relatively less affected by variability in earth slope properties. Their conclusion is consistent with the findings of Yegian et al. (1991). Uncertainty in GM characterization is thus far the dominant source of inaccuracy when calculating seismic displacements (Bray and Travasarou, 2007). Among the simplified procedures for estimating seismic slope displacement, researchers have used PGA as the primary GM intensity measure. PGA is sometimes supplemented by additional parameters that characterize the frequency content and duration of GM. For example, Makdisi and Seed (1978) employed earthquake magnitude (Mw) as a proxy for duration in combination with estimated PGA at the crest of embankment. Yegian et al. (1991) utilized predominant period (T_p) and the equivalent number of loading cycles in combination with PGA. Bray and Rathje (1998) employed mean period (T_m) and significant duration of the design rock motion in combination with PGA. The prediction equation by Jibson et al. (2000) includes area intensity (Ia) and PGA as key parameters for predicting estimated displacements.

Saygili and Rathje (2008) concluded that GM parameters PGA with PGV are sufficient to predict sliding displacement. Hsieh and Lee (2011) proposed a new form for the relationship among Ia and displacement. They basically introduced a third term in addition to the form developed by Jibson et al. (1998) to differentiate the displacement caused by GMs at rock and soil sites. Different models for rock and soil sites indicate the insufficiency in using Ia and ky for predicting displacement. The model developed by Bray and Travasarou (2007) that is founded on the condition on the fundamental period of sliding mass (T_s) and the spectral acceleration at 1.5Ts also shows bias toward the site period. Therefore, other GM parameters that reflect site conditions (e.g., T_m) should be considered.

2.2. Newmark displacement database

The database used in developing the prediction models is classified into two categories, namely, case history and numerical simulation. The empirical method based on case histories (e.g., Jibson et al., 2000) is limited to a number of cases in the database because it directly uses data history. Moreover, only a single event is often considered, such that the different magnitudes and motion durations are disregarded in the model. By contrast, the numerical simulation approach considers