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Recent Advances in Predicting Earthquake-Induced Sliding Displacements of Slopes

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RECENT ADVANCES IN PREDICTING EARTHQUAKE-INDUCED SLIDING DISPLACEMENTS OF SLOPES

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ABSTRACT

This paper summarizes recent research related to predicting earthquake-induced sliding displacements of earth slopes. Recently developed empirical models for the prediction of sliding displacements for shallow (rigid) failure surfaces are discussed, and comparisons of the different models demonstrate that including peak ground velocity, along with peak ground acceleration, reduces the median displacement prediction and the standard deviation of the prediction. Thus, peak velocity provides important information regarding the level of sliding displacement. A framework is developed such that the recently developed empirical displacement models for rigid sliding can be used for deeper, flexible failure surfaces, where the dynamic response of the sliding mass is important. This framework includes predicting the seismic loading for the sliding mass in terms of the maximum seismic coefficient (k_{max}) and the maximum velocity of the seismic coefficient-time history (k-vel$_{max}$). The predictive models for k_{max} and k-vel$_{max}$ are a function of the peak ground acceleration (PGA), peak ground velocity (PGV), the natural period of the sliding mass (T_s), and the mean period of the earthquake motion (T_m). With a slight modification, the empirical predictive models for rigid sliding masses can be used, with PGA replaced by k_{max} and PGV replaced by k-vel$_{max}$. The standard deviations for the modified predictive models for flexible sliding masses are slightly smaller than those for rigid sliding masses.

INTRODUCTION

Permanent sliding displacement represents the preferred damage parameter for evaluating the seismic stability of slopes. This displacement represents the cumulative, downslope movement of a sliding mass due to earthquake shaking. The magnitude of sliding displacement relates well with observations of seismic performance (e.g., Jibson et al. 2000), and thus has been a useful parameter in seismic design.

Figure 1 outlines the process used to compute the earthquake-induced sliding displacement (D) of a slope with yield acceleration, k_y (k_y = seismic coefficient that yields a factor of safety of 1.0). If the sliding mass is relatively shallow and stiff, a rigid sliding block analysis is appropriate. In this case, the dynamic response of the sliding mass is ignored because it is considered negligible. The seismic loading is simply the acceleration-time (a-t) history at the base of the sliding mass, with the slope's destabilizing force equal to the acceleration (in units of gravity, g) times the weight of the sliding mass. Seismic loading parameters can be derived from the acceleration-time history and these parameters represent various ground motion characteristics (GM), such as peak ground acceleration (PGA), peak ground velocity (PGV), etc. The seismic loading parameters are used, along with the k_y of the slope, to predict D from empirical models (e.g., Jibson 2007).

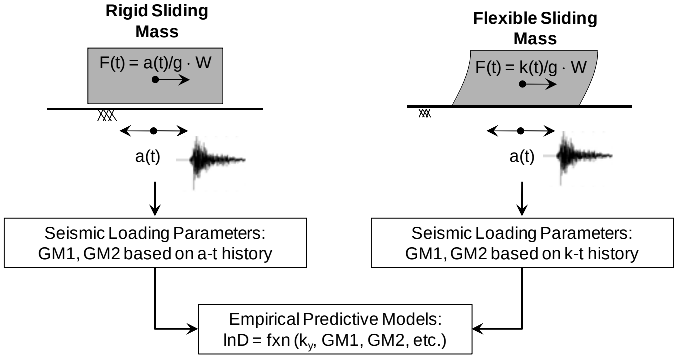


Fig. 1. Process for computing earthquake-induced sliding displacements for rigid and flexible sliding masses.

If the sliding mass is deeper and/or softer, the rigid sliding block model is not appropriate and the dynamic response of the flexible sliding mass must be taken into account (Fig. 1). A decoupled sliding block analysis (e.g., Makdisi and Seed 1978, Bray and Rathje 1998) computes the dynamic response of the sliding mass without any consideration of the sliding displacement, and then uses the results of the dynamic response analysis to compute the sliding displacement. A coupled analysis (e.g., Rathje and Bray 1999, 2000) simultaneously computes the dynamic and sliding responses. Within either approach, the seismic loading for the sliding mass is the seismic coefficient (k)-time history, in which k represents the average acceleration within the sliding mass as well as the shear force at the base of the sliding mass. For a coupled analysis, k cannot exceed k_y, and the dynamic equations of equilibrium change during sliding to enforce this condition. For a decoupled analysis, the k-time history may exceed k_y, and the k-time history is used in a rigid sliding block analysis in lieu of the a-time to compute displacements.

This paper discusses recently developed empirical models for rigid sliding displacement (i.e., Saygili and Rathje 2008, Rathje and Saygili 2009) that use multiple ground motion parameters to predict sliding displacement. A modification to these models is described that incorporates the dynamic response of flexible sliding masses and, as a result, the models provide an estimate of decoupled sliding displacements. The modification involves predicting the seismic loading parameters of a flexible sliding mass in terms of the same ground motion parameters used for rigid sliding masses, except that these parameters are computed from the k-time history rather than the a-time history. Predictive models for these seismic loading parameters are provided, and the rigid sliding block empirical models are modified slightly.

RIGID SLIDING BLOCK DISPLACEMENTS

Saygili and Rathje (2008) presented a suite of empirical predictive models for the sliding displacement of slopes, and these models incorporate different ground motion parameters, such as PGA, PGV, Mean Period (T_m, Rathje et al. 2004), and Arias Intensity (I_a), as well as combinations of these ground motion parameters. Rathje and Saygili (2009) slightly modified the PGA model from Saygili and Rathje (2008) by adding a term related to earthquake magnitude (M). The Rathje and Saygili (2009) modification is repeated in Rathje and Saygili (2010). The recommended single (scalar) parameter model is the (PGA, M) model from Rathje and Saygili (2009), and the recommended two (vector) parameter model is the (PGA, PGV) model from Saygili and Rathje (2008). For simplicity, these models will be called the SR08/RS09 models.

Figure 2 plots predicted values of D from the SR08/RS09 models as a function of k_y for different earthquake scenarios of M = 6, 7, and 8, each with the distance (R) equal to 2 km and Vs30 equal to 750 m/s. The Boore and Atkinson (2008) ground motion prediction equation was used to predict the median values of PGA and PGV for each earthquake scenario, and these values are listed in Table 1. Note that the PGA values begin to saturate at larger magnitudes, while the PGV values continue to rise. The predicted values of D in Fig. 2 are shown for both the (PGA, M) and (PGA, PGV) models. For M=6, the (PGA, M) and (PGA, PGV) models predict similar displacements, but the displacements become more different as earthquake magnitude, and the associated PGV, increases. The (PGA, PGV) model generally predicts smaller displacements for these scenarios, on the order of 30 to 40% smaller. These differences are caused by the fact that the empirical models were developed using rock and soil motions from the large Next Generation Attenuation ground motion dataset. Because soil motions tend to have larger PGV values than rock motions and the (PGA, M) model does not include the effects of PGV, the (PGA, M) model predicts larger displacements than the (PGA, PGV) model for rock sites. The differences are much smaller when utilizing ground motion parameters for soil sites.

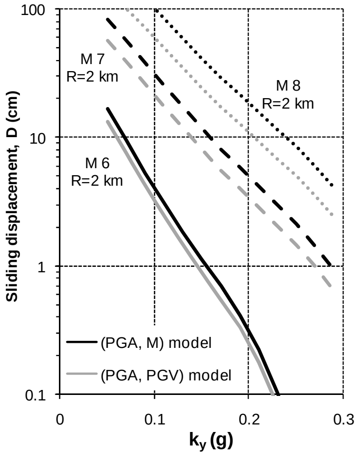


Fig. 2. Rigid sliding block displacements calculated from the (PGA, M) and (PGA, PGV) models for different earthquake scenarios.

Table 1. Ground motion parameters for each earthquake scenario (Vs30 = 750 m/s)

M	**R (km)**	**PGA (g)**	**PGV (cm/s)**
6.0	2	0.30	19
7.0	2	0.43	42
8.0	2	0.48	74

In addition to the differences in median displacements from the (PGA, M) and (PGA, PGV) models, there are significant differences in the standard deviations of the predictions. The standard deviation ($\sigma_{\ln D}$) for each model increases with increasing k_y/PGA, with values ranging between 0.75 and 1.0 (in natural log units) for the (PGA, M) model, and values ranging between 0.4 and 0.9 for the (PGA, PGV) model. To illustrate these differences, the median and $\pm1\sigma_{\ln D}$ displacements for the (PGA, M) and (PGA, PGV) models are shown in Fig. 3 for the M = 7, R = 2 km scenario event. At larger k_y, the $\pm1\sigma_{\ln D}$ range in displacement is close to a factor of 10 for the (PGA, M) model, and it decreases to a factor of about 5 at smaller k_y. For the (PGA, PGV) model, the $\pm1\sigma_{\ln D}$ displacement range is much smaller by comparison, with the range representing a factor of 2.5 at smaller k_y and a factor of 4.0 at larger k_y. Thus, there is significantly less uncertainty in the displacement prediction when PGV is used in the displacement calculation.

One shortcoming of the SR08/RS09 empirical models is that they only represent rigid sliding block conditions. Flexible sliding block conditions are very common, and it would be beneficial to be able to use the SR08/RS09 models for flexible sliding conditions. However, application of the SR08/RS09 models to flexible sliding conditions requires appropriate quantification of the seismic loading.

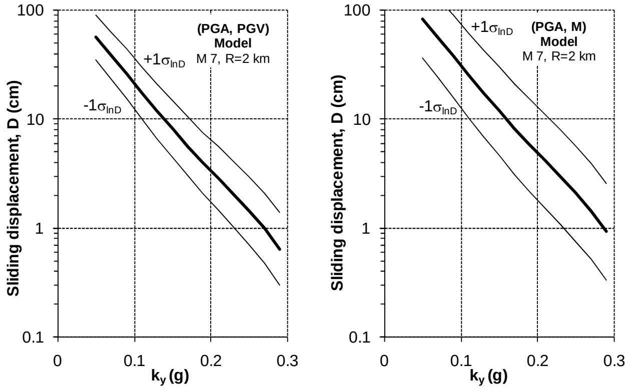
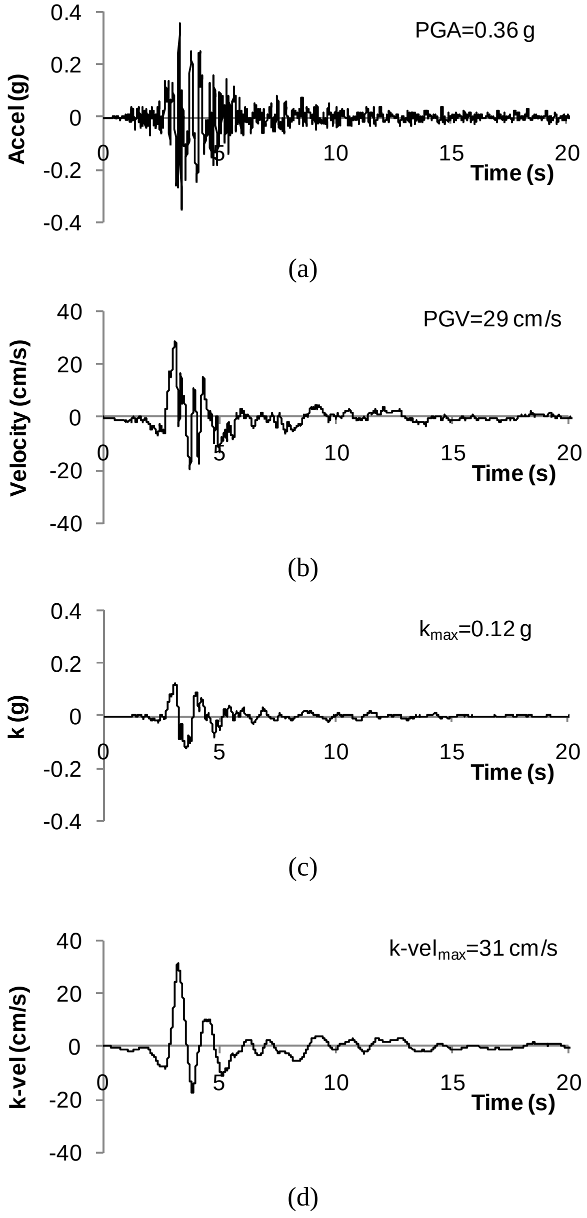


Fig. 3. Median and $\pm1\sigma_{\ln D}$ rigid sliding block displacements predicted by the (PGA, M) and (PGA, PGV) models for M = 7, R = 2 km.

SEISMIC LOADING PARAMETERS FOR FLEXIBLE SLIDING MASSES

The SR08/RS09 models use (PGA, M) and (PGA, PGV) to characterize the seismic loading for rigid sliding blocks. Figure 4a shows the GIL067 acceleration-time history recorded during the 1989 Loma Prieta (M=6.9) earthquake, and Fig. 4b shows the velocity-time history derived from numerical integration of the acceleration-time history. These time histories display PGA = 0.36 g and PGV = 29 cm/s, and the acceleration-time history represents the seismic loading for a rigid sliding block.

The seismic loading for a flexible sliding mass subjected to the GIL067 motion will not be the acceleration-time history shown in Fig. 4a because of the dynamic response of the sliding mass. Rather, the seismic loading is the k-time history (e.g., Seed and Martin 1966, Bray and Rathje 1998), which represents the average acceleration within the sliding mass as well as the shear force at the base of the sliding mass. Consider the dynamic response of a 30-m thick sliding mass (H = 30 m) with a shear wave velocity of 250 m/s (Vs = 250 m/s) and associated site period of 0.5 s (T_s = 4H/Vs = 0.5 s). The k-time history for this site, computed using one-dimensional, equivalent-linear site response analysis, is shown in Fig. 4c. Note that the k-time history displays much less high frequency motion than the acceleration-time history due to the averaging of accelerations within the sliding mass, and its peak value (k_{max}) is smaller than the input PGA (k_{max} = 0.12 g vs. PGA = 0.36 g). The k-time history and its associated



(a)

(b)

(c)

(d)

Fig. 4. (a) Acceleration and (b) velocity-time histories for a rigid sliding block. (c) k-time history and (d) k-vel-time history for a flexible sliding mass with T_s=0.5 s.

k_{max} represent the appropriate seismic loading for this flexible sliding mass.

In the same way that an acceleration-time history can be numerically integrated to generate a velocity-time history, the k-time history can be numerically integrated to generate a velocity-time history of the k-time history. This velocity is called k-vel, and while it does not represent the average velocity of motion with the sliding mass, it does provide information regarding the frequency content of the k-time history. The maximum value of the k-vel-time history is called k-vel$_{max}$. As expected, the k-vel-time history contains less high frequency motion than the velocity-time history. Surprisingly, however, the value of k-vel$_{max}$ (31 cm/s) is similar to the value of PGV (29 cm/s). Because the integrated k-vel-time history is influenced by both the amplitude and frequency content of the k-time history, the increase in long period motion in the k-time history is balanced by the reduction in its peak such that k-vel$_{max}$ is similar in amplitude to PGV.

To use the SR08/RS09 predictive models for flexible sliding blocks, the appropriate seismic loading parameters must be specified. Based on the above descriptions, k_{max} should be used to replace PGA in the SR08/RS09 models and k-vel$_{max}$ should be used to replace PGV. Earthquake magnitude does not need to be modified.

Predictive models for k_{max} and k-vel$_{max}$ are required such that engineers do not need to perform dynamic response analysis to estimate the seismic loading parameters for the SR08/RS09 models. These predictive models are along the same lines as Bray and Rathje (1998) and Bray et al. (1998), but they also include predictions for k-vel$_{max}$.

The predictive models were developed based on one-dimensional site response calculations of five sites subjected to 80 input motions using the equivalent-linear site response code Strata (Kottke and Rathje 2008). The sites consisted of one 15-m profile (Vs = 400 m/s), two 30-m profiles (Vs = 400 m/s and 250 m/s) and two 100-m profiles (Vs = 400 m/s and 265 m/s). The resulting values of site period (T_s) were 0.15 s, 0.30 s, 0.48 s, 1.0 s, and 1.5 s. The nonlinear soil properties were modeled with the curves of Darendeli and Stokoe (2001) using PI = 0 and appropriate values of confining pressure. The 80 input motions represent motions from M = 6 to 7.9 earthquakes recorded a distances between 0.1 and 60 km with Vs30 = 200 to 1000 m/s. However, most of the Vs30 values are between 400 and 800 m/s. The input PGA values ranged from 0.02 to 1.0 g, and the input PGV values ranged from 1.2 cm/s to 70 cm/s. k-time histories were computed at the base of each one-dimensional site profile. Further details about the analyses performed can be found in Antonakos (2009).

The computed k_{max} values are plotted versus input rock PGA in Fig. 5a for the 400 analyses performed. There is trend of increasing k_{max} with increasing PGA, although at a decreasing rate and with more scatter at larger values of PGA. Bray and Rathje (1998) investigated the ratio of k_{max} to PGA and showed that the period ratio (T_s/T_m) has a strong influence on this value. k_{max} / PGA is plotted versus T_s/T_m in Fig. 5b, and several important observations can be made. First, k_{max} / PGA approaches 1.0 as T_s/T_m approaches 0.1. This trend is consistent with k_{max} = PGA for rigid sliding masses, and indicates that T_s/T_m = 0.1 essentially represents rigid sliding conditions. Next, k_{max} is greater than PGA at moderate period ratios, while k_{max} is less than PGA at larger period ratios. Finally, k_{max} / PGA decreases with increasing PGA.

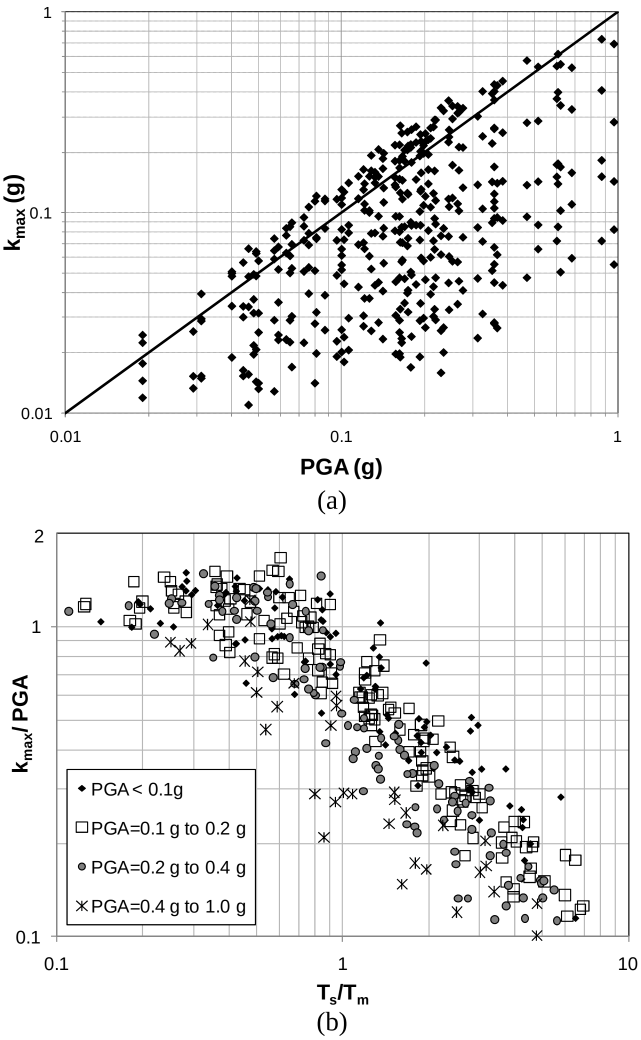


Fig. 5. (a) Variation of k_{max} with PGA, and (b) k_{max}/PGA vs. T_s/T_m

A predictive equation for k_{max} / PGA is developed to model these trends:

$$\ln(k_{max}/PGA) = (0.459 - 0.702\cdot PGA)\cdot\{\ln([T_s/T_m]/0.1)\} + (-0.228 + 0.076\cdot PGA)\cdot\{\ln([T_s/T_m]/0.1)\}^2 \quad \text{for } T_s/T_m \geq 0.1 \qquad (1a)$$

$$\ln(k_{max}/PGA) = 0 \qquad \text{for } T_s/T_m < 0.1 \qquad (1b)$$

The standard deviation for this model in natural log units is 0.25. Given the predicted value of k_{max} / PGA and the input motion PGA, k_{max} can be estimated.

Figure 6 presents the model predictions of k_{max} / PGA as a function of input PGA and T_s/T_m. Generally, k_{max} / PGA is greater than 1.0 at smaller values of T_s/T_m, and then falls below 1.0 at larger period ratios. The T_s/T_m range of amplification decreases with increasing PGA, and at large values of PGA there is no period range of amplification. All curves predict k_{max} / PGA = 1.0 for $T_s/T_m \leq 0.1$.

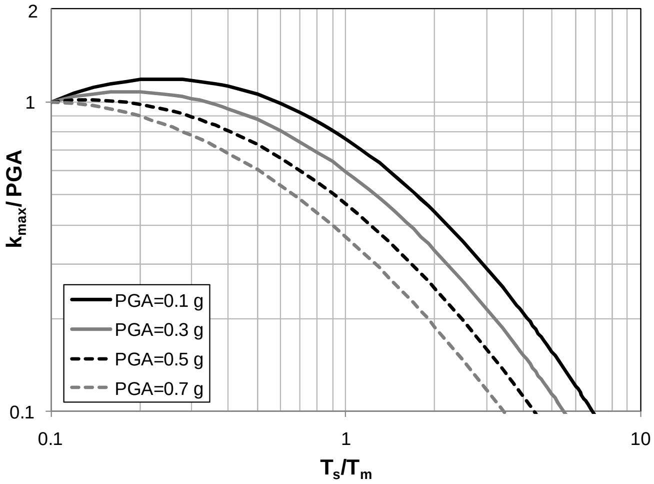


Fig. 6. k_{max} / PGA model predictions from equation (1)

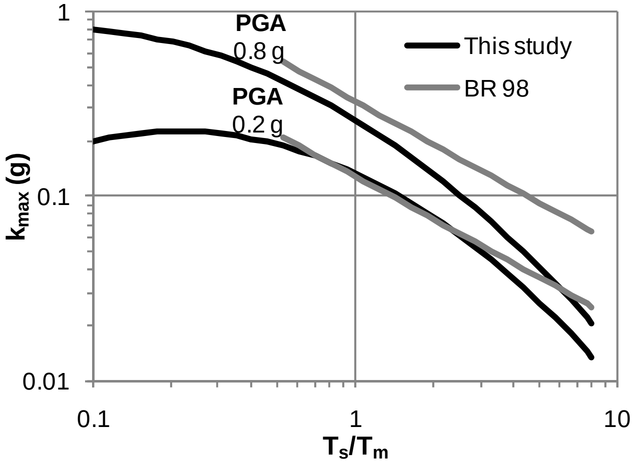
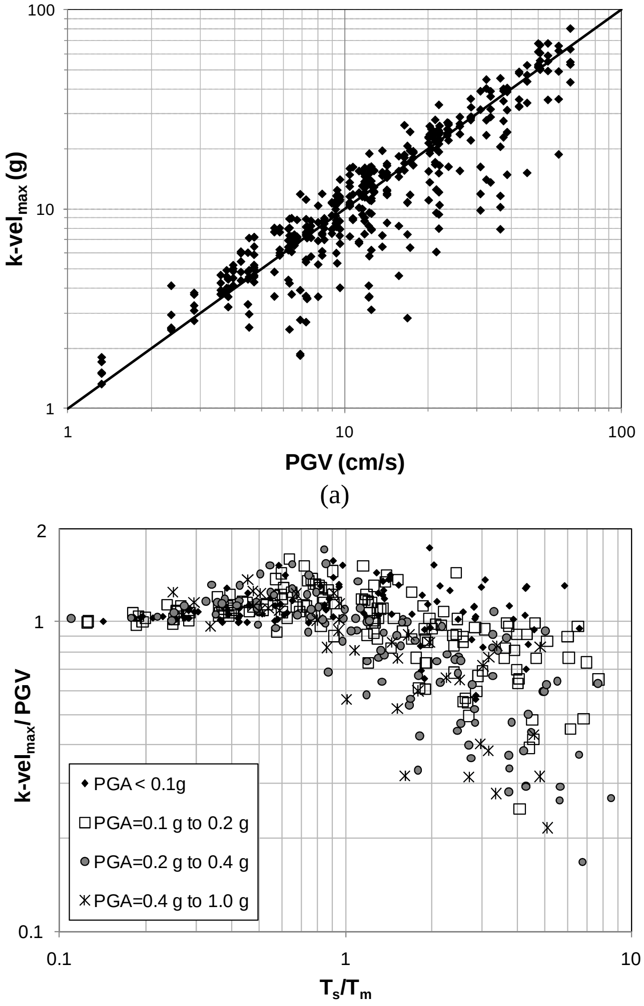


Fig. 7. Comparisons of k_{max} predictions from equation (1) and from Bray and Rathje (1998)

Bray and Rathje (1998) developed a predictive model for k_{max} that uses a power law relationship to predict a normalized k_{max} (k_{max} / [NRF·PGA]) as a function of T_s/T_m. The power law relationship results in a log-linear relationship between k_{max} and T_s/T_m for a constant value of PGA. The PGA normalization effectively scales k_{max} linearly with PGA, although the nonlinear response factor (NRF) takes into account some nonlinear scaling. The predictive model from (1) is compared to the predictions from Bray and Rathje (1998) in Fig. 7 for input PGA values of 0.2 and 0.8 g. The Bray and Rathje (1998) predictions are generally larger than those from equation (1), mostly due to the power law relationship used in the model. The two models are similar for T_s/T_m between 0.5 and 2.0, but equation (1) from this study predicts smaller values of k_{max} at larger and smaller values of period ratio. This difference is due to the second-order polynomial used in equation (1) for the functional form, which more accurately models the variation of k_{max} / PGA over a wide range of period ratios.



(a)

(b)

Fig. 8. (a) Variation of k-vel$_{max}$ with PGV, and (b) k-vel$_{max}$ / PGV vs. T_s/T_m

The additional information required to use the SR08/RS09 predictive models is k-vel$_{max}$. Figure 8a shows the computed values of k-vel$_{max}$ versus PGV. Based on the example shown in Fig. 4, we should not expect significant differences in k-vel$_{max}$ and PGV, and the data confirm this expectation. A significant amount of data centers about a 1:1 line, with some considerably smaller values associated with the softest site. To further explore this variability, the ratio of k-vel$_{max}$ to PGV was computed for each motion and plotted versus T_s/T_m (Fig. 8b). Similar to the k_{max} / PGA data, the k-vel$_{max}$ data indicate k-vel$_{max}$ greater than PGV at smaller period ratios and k-vel$_{max}$ less than PGV at larger period ratios. The range of period ratios where amplification occurs is larger for k-vel$_{max}$ than for k$_{max}$, and k-vel$_{max}$ approaches PGV at $T_s/T_m = 0.2$. Again, there is an intensity effect, with smaller values of k-vel$_{max}$ / PGV observed at larger values of input PGA.

A predictive model for k-vel$_{max}$ / PGV was developed with a similar functional form to equation (1). Because the intensity effect for k-vel$_{max}$ / PGV is not significant at small period ratios (Fig. 8b), only the coefficient for the second-order term is dependent on PGA. The predictive model for k-vel$_{max}$ / PGV is:

$$\ln(\text{k-vel}_{max}/PGV) = (0.240) \cdot \{ \ln([T_s/T_m]/0.2) \} + (-0.091 - 0.171 \cdot PGA) \cdot \{ \ln([T_s/T_m]/0.2) \}^2 \quad \text{for } T_s/T_m \geq 0.2 \tag{2a}$$

$$\ln(\text{k-vel}_{max}/PGV) = 0 \quad \text{for } T_s/T_m < 0.2 \tag{2b}$$

The standard deviation for this model in natural log units is 0.25.

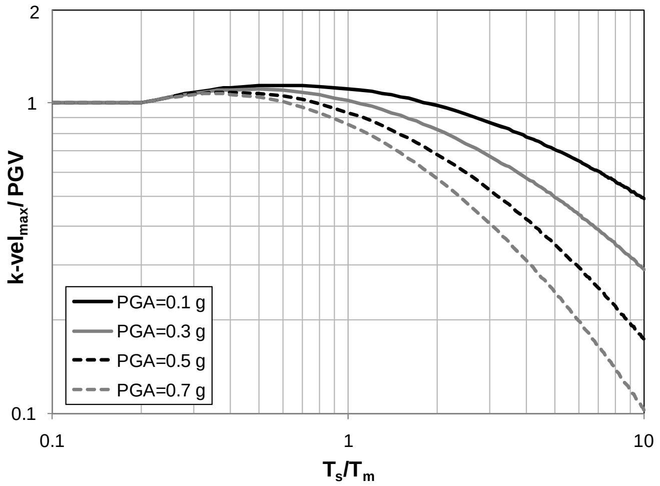


Fig. 9. k-vel$_{max}$ / PGV model predictions from equation (2)

Figure 9 presents the model predictions of k-vel$_{max}$ / PGV as a function of input PGA and T_s/T_m. Generally, k-vel$_{max}$ / PGV is similar for all input intensities at period ratios less than 0.3. At larger period ratios, k-vel$_{max}$ / PGV is smaller for larger input intensities. The model predicts k-vel$_{max}$ / PGV = 1.0 for $T_s/T_m \leq 0.2$.

DISPLACEMENT PREDICTIONS FOR FLEXIBLE SLIDING MASSES

The objective of this study is to modify the SR08/RS09 empirical models for rigid sliding displacement such that they can be used to predict the decoupled displacements of flexible sliding systems. The initial premise is that the original SR08/RS09 empirical models can be used, but with PGA replaced by k$_{max}$ and PGV replaced by k-vel$_{max}$. To test this hypothesis, decoupled sliding displacements were calculated using the computed k-time histories for the five sites and 80 input motions. Displacements were calculated for $k_y = 0.04$, 0.08, 0.12, and 0.16. The resulting dataset included 569 non-zero values of displacement (i.e., instances where $k_y < k_{max}$). These values of displacement were compared with the median values predicted by the SR08/RS09 empirical models using the computed values of k$_{max}$ and k-vel$_{max}$ for each calculated k-time history.

The residuals (i.e., ln(data) – ln(predicted)) of the computed values of D (i.e., data) with respect to the predicted values of D were calculated for both the (PGA, M) model and the (PGA, PGV) model. For both models, the average residuals over the complete dataset are greater than 0.0, with an average of 0.24 for the (PGA, M) model and an average of 0.42 for the (PGA, PGV) model. These positive values indicate that the computed values of D are larger, on average, than the values predicted by the SR08/RS09 empirical models. The difference is caused by the fact that the frequency content of a k-time history is significantly different than for an acceleration-time history (Fig. 4), which results in larger displacements. While k-vel$_{max}$ attempts to take into account this difference in frequency content, the time histories in Fig. 4 demonstrate that PGV and k-vel$_{max}$ do not vary significantly from one another although the k-time time histories display significantly different frequency contents. Nonetheless, the residuals can be used to modify the original SR08/RS09 empirical models for this effect.

The residuals were investigated to identify the site/ground motion parameters that influence the difference between the computed and predicted displacements. Figure 10 plots the residuals vs. site period for the two displacement models. These data indicate that the residuals increase with increasing site period (T_s), but at a decreasing rate. The residuals increase with T_s because larger values of T_s generate k-time histories with more long period energy that lead to larger displacements. The scatter at any one period in Fig. 10 is larger for the (PGA, M) model than the (PGA, PGV) model, and this observation is consistent with the relative values of σ_{lnD} reported for the two models. Also included in Fig. 10 are the residuals for the 80 acceleration time histories under rigid sliding block condition ($T_s = 0.0$ s). The average residuals for rigid sliding block conditions should be equal to 0.0.

Considering the (PGA, M) model (Fig. 10a), the average residual for $T_s = 0.0$ s is -0.8. This value is non-zero because the average Vs30 for the motions used in this study is larger than for those used in the SR08/RS09 studies. For larger T_s values, the average residual is as large as 1.95. A second order polynomial was fit to the average residuals, and this expression can be used to modify the SR08/RS09 (PGA, M) rigid sliding block model for the effects of decoupled, flexible sliding. However, the residuals in Fig 10a are influenced by the fact that the ground motion dataset is not fully consistent with the dataset used in the SR08/RS09 studies (i.e., average

Vs30 is different, average residual is not equal to zero at T_s = 0.0 s). Therefore, the recommended modification involves translating the curve shown in Fig. 10a such that the average residual is equal to zero at T_s = 0.0 s. The resulting modification to the SR08/RS09 (PGA, M) model to account for flexible sliding is:

$$\ln(D_{flexible}) = \ln(D_{PGA,M}) + 3.69 \cdot T_s - 1.22 \cdot (T_s)^2 \quad \text{for } T_s \leq 1.5 \qquad (3a)$$

$$\ln(D_{flexible}) = \ln(D_{PGA,M}) + 2.78 \quad \text{for } T_s > 1.5 \qquad (3b)$$

where $D_{PGA,M}$ represents the median displacement predicted by the (PGA, M) SR08/RS09 rigid sliding block model and T_s is the natural period of the sliding mass. For the calculation of $D_{PGA,M}$, k_{max} is used in lieu of PGA.

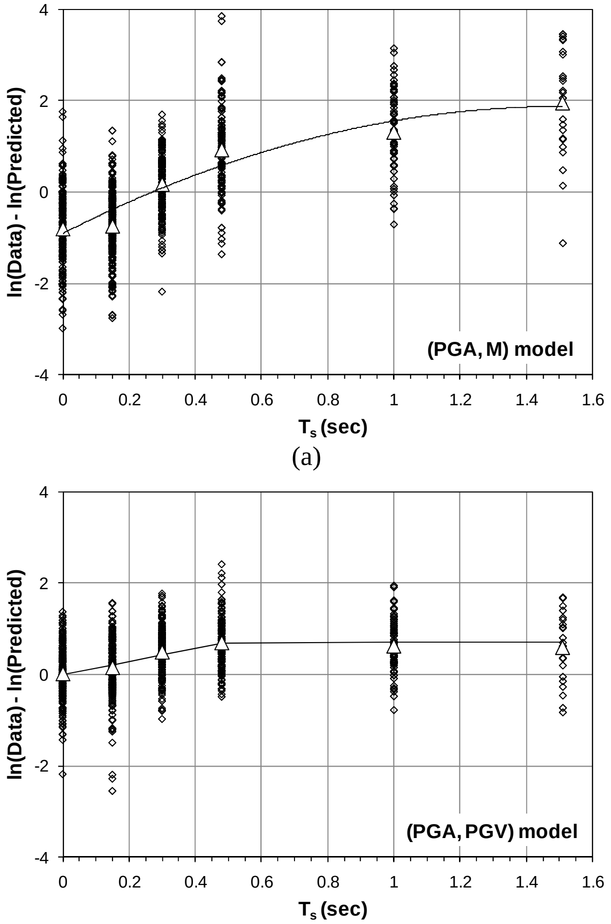


Fig. 10. (a) Displacement residuals vs. T_s for the (PGA, M) model and (b) Displacement residuals vs. T_s for the (PGA, PGV) model

Considering the (PGA, PGV) model (Fig. 10b), the average residual for T_s = 0.0 s is essentially zero. The Vs30 effect is not apparent for this model because the inclusion of PGV takes into account the different frequency contents for rock and soil motions. The average residuals increase with increasing T_s, but become relatively constant at periods greater than 0.5 s. A linear relationship was fit through the average residuals at $T_s \leq 0.5$ s, with no further increase at larger periods. The resulting modification to the SR08/RS09 (PGA, PGV) model to account for flexible sliding is:

$$\ln(D_{flexible}) = \ln(D_{PGA,PGV}) + 1.42 \cdot T_s \quad \text{for } T_s \leq 0.5 \qquad (4a)$$

$$\ln(D_{flexible}) = \ln(D_{PGA,PGV}) + 0.71 \quad \text{for } T_s > 0.5 \qquad (4b)$$

where $D_{PGA,PGV}$ represents the median displacement predicted by the (PGA, PGV) SR08/RS09 rigid sliding block model and T_s is the natural period of the sliding mass. For the calculation of $D_{PGA,PGV}$, k_{max} is used in lieu of PGA and $k\text{-}vel_{max}$ is used in lieu of PGV.

After correcting the biases observed in the residuals shown in Fig. 10, the standard deviation of lnD (σ_{lnD}) was computed from the corrected residuals. Considering that the SR08/RS09 models display a variation of σ_{lnD} with k_y/PGA, the models from this study should display a variation of σ_{lnD} with k_y/k_{max}. The computed values of σ_{lnD} are plotted versus k_y/k_{max} in Fig. 11 for the (PGA, M) and (PGA, PGV) models. The σ_{lnD} values for the (PGA, M) model follow a linear trend (Fig. 11a), and are about 10% smaller than σ_{lnD} values from the SR08/RS09 model. The reduction in standard deviation for flexible sliding masses is expected because the dynamic response calculation filters out the high frequency peaks that contribute to the variability in predicting rigid block displacements. The recommended σ_{lnD} relationship for the (PGA, M) model for flexible sliding masses is given by:

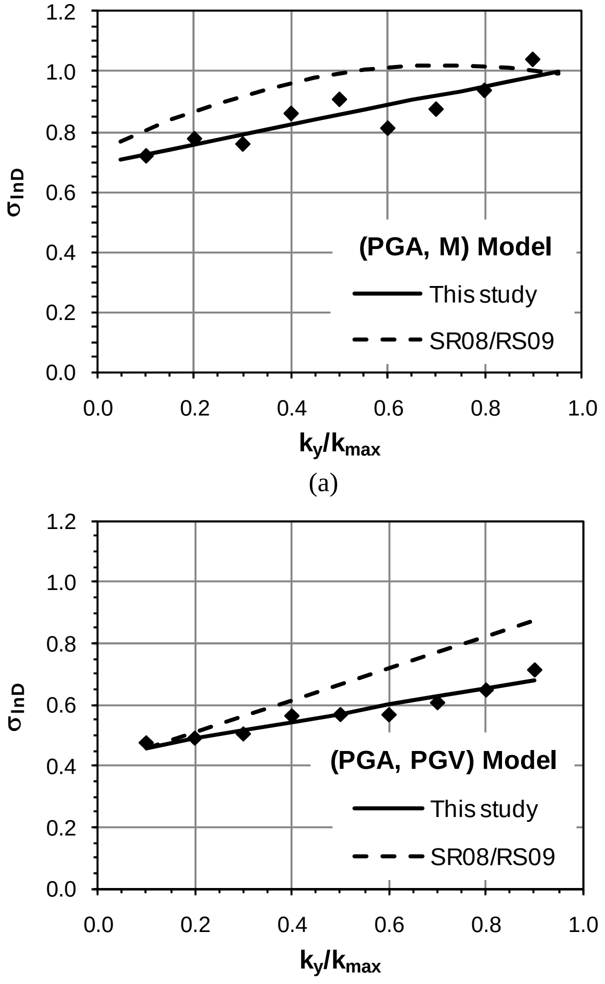
$$\sigma_{lnD} = 0.694 + 0.322 \cdot k_y/k_{max} \quad \text{for (PGA, M) model} \qquad (5)$$

The σ_{lnD} values for the (PGA, PGV) model (Fig. 10b) are also smaller than those from SR08/RS09, particularly at large values of k_y/k_{max}. A revised linear relationship is used to predict σ_{lnD} for flexible sliding masses for the (PGA, PGV) model:

$$\sigma_{lnD} = 0.40 + 0.284 \cdot k_y/k_{max} \quad \text{for (PGA, PGV) model} \qquad (6)$$

EXAMPLE APPLICATIONS

To illustrate the developed modifications, consider a flexible sliding mass 20-m thick with Vs = 400 m/s resulting in T_s = 0.2 s. The k_y is equal to 0.1. The design event is M = 8 and R = 2 km, with the input rock motions described by Table 1 (PGA=0.48g, PGV=74 cm/s) and with T_m = 0.46 s (Rathje et



(a)

(b)

Fig. 11. (a) Standard deviation of lnD for flexible sliding masses using (PGA, M) model, (b) standard deviation of lnD for flexible sliding masses using (PGA, PGV) model

al. 2004). Based on the site and ground motion characterizations, $T_s/T_m = 0.43$.

Equations 1 and 2 are used to predict k_{max} and k-vel$_{max}$ based on the PGA (0.48 g), PGV (74 cm/s), and T_s/T_m (0.43). Using these values, equation 1 predicts k_{max}/PGA = 0.79, while equation 2 predicts k-vel$_{max}$/PGV = 1.08. Thus, k_{max} is equal to 0.38 g (=0.79 · 0.48 g) and k-vel$_{max}$ is equal to 80 cm/s (=1.08 · 74 cm/s).

Using the seismic loading parameters of k_{max} = 0.38 g and M = 8 along with k_y = 0.1, the SR08/RS09 (PGA, M) model predicts 63.1 cm when k_{max} is used in lieu of PGA. This value must be adjusted using the modification for flexible sliding given in equation (3). For T_s = 0.2 s, this expression predicts a displacement value of 126 cm for flexible sliding conditions.

For the SR08/RS09 (PGA, PGV) model, the appropriate seismic loading parameters are k_{max} = 0.38 g and k-vel$_{max}$ = 80 cm/s. Using k_{max} in lieu of PGA and k-vel$_{max}$ in lieu of PGV in the SR08/RS09 (PGA, PGV) model predicts a displacement of 36.9 cm. Adjusting this value for flexible sliding and T_s = 0.2 s (equation 4), the predicted value of displacement is 49 cm for flexible sliding conditions.

Figure 12 plots the predicted displacements for this equation scenario (M = 8, R =2 km, k_y = 0.1) as a function of T_s between 0 (rigid sliding) and 1.0 s. For all periods, the modified (PGA, M) model predicts larger displacements than the modified (PGA, PGV) model. This observation is similar to that found for rigid sliding, and it is caused by the lack of information about frequency content incorporated into the (PGA, M) model. For both models, the flexible displacements are larger than the rigid displacements at smaller values of T_s, but then become smaller as the dynamic response of the sliding mass results in smaller values of k_{max}. For this scenario, k_{max} falls below 0.1 (i.e., the k_y value) at T_s ~ 1.15 s.

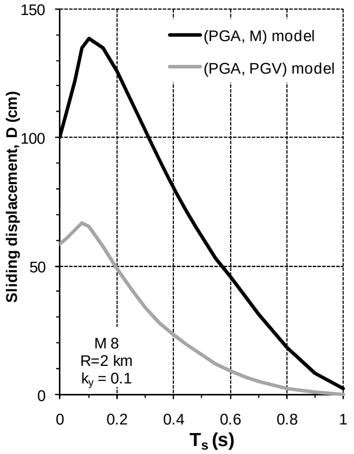


Fig. 12. Predicted values of displacement as a function of T_s for the modified (PGA, M) model and the modified (PGA, PGV) model.

CONCLUSIONS

Saygili and Rathje (2008) and Rathje and Saygili (2009) recently developed improved empirical models for predicting the earthquake-induced permanent sliding displacements of slopes. The SR08/RS09 models incorporate various ground motion parameters, and the (PGA, M) and (PGA, PGV) models were recommended for use. The main advancements contributed by the SR08/RS09 models include: (1) the use of a large ground motion dataset, (2) the addition of a frequency content parameter (PGV) to better predict displacements, and (3) a better description of the standard deviation associated with each model.

The main shortcoming of the SR08/RS09 models is that they only apply to rigid sliding block conditions. This paper presents a framework to extend these models to flexible sliding block conditions. This framework involves predicting the seismic loading parameters in terms of k_{max} and k-vel$_{max}$, defined as the maximum value of the k-time history and the maximum velocity of the k-time history, respectively. A predictive model for k_{max} was developed as a function of PGA and T_s/T_m, and a predictive model for k-vel$_{max}$ was developed as a function of PGV, PGA, and T_s/T_m. To predict sliding displacement, k_{max} is used in lieu of PGA and k-vel$_{max}$ is used in lieu of PGV in the SR08/RS09 models.

In addition to the change in seismic loading parameters, the SR08/RS09 models must be further modified to account for the differences in frequency characteristics between acceleration-time histories and k-time histories. This modification is a function of T_s and increases the predicted displacement. The standard deviations of the predictions are reduced for flexible sliding, as compared to rigid sliding.

The developed framework provides a continuous description of the dynamic response for rigid through flexible conditions, and the prediction of displacement takes advantage of the improvements introduced by Saygili and Rathje (2008) and Rathje and Saygili (2009). Because of the significant frequency content information provided by PGV (for rigid sliding) and by k-vel$_{max}$ (for flexible sliding), the (PGA, PGV) model is recommended over the (PGA, M) model for future use.

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