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SIMPLIFIED PROCEDURE FOR ESTIMATING SEISMIC SLOPE DISPLACEMENTS IN SUBDUCTION ZONES

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Abstract

A simplified procedure for estimating seismic shear-induced permanent displacements in subduction earthquake zones is presented. It may be applied to assess the seismic performance of an earth/rockfill dam, natural slope, heap leach pads, or solid-waste landfill. The new procedure uses the framework of the widely used Bray and Travasarou [1] simplified method (BT07). The primary source of uncertainty in assessing the likely performance of an earth slope or system during an earthquake is the input ground motion. Hence, a comprehensive database containing 1620 recorded ground motions from subduction zone interface earthquakes was developed and used to compute seismic slope displacements. The proposed seismic slope displacement model captures the primary influence of the system's yield coefficient k_y, its initial fundamental period T_s, and the ground motion's spectral acceleration at a degraded period of the slope taken as $1.5T_s$. The model separates the probability of "zero" displacement (i.e., < 1 cm) from the distribution of "nonzero" displacement, so that low values of calculated seismic displacement do not bias the results. The new seismic displacement model better captures the unique seismic setting of subduction earthquakes. The BT07 procedure, which was developed using only shallow crustal earthquake records, tends to overestimate seismic displacements (if applied to subduction settings) relative to the new model which was developed using subduction zone earthquake records. Reasons for the differences in the two models are discussed. The proposed model can be implemented rigorously within a fully probabilistic framework or used deterministically to evaluate seismic displacement potential.

Keywords: Subduction settings, Seismic displacement, Seismic Performance.

1. Introduction

Engineers often employ simplified Newmark-type seismic slope displacement procedures to evaluate the seismic performance of geotechnical structures (i.e., earth/rockfill dam, solid-waste landfill, natural earth slope, heap leach pad, or constructed earth embankment). However, most of these procedures were developed using earthquake ground motions from shallow crustal earthquakes along active plate margins (e.g., California earthquakes). Some examples of these procedures are Bray and Travasarou [1], Jibson [2], Rathje and Antonakos [3], among others.

These semi-empirical procedures should not be applied directly to other seismotectonic settings (such as subduction earthquake zones) nor extrapolated without evaluating their applicability for settings for which they were not originally developed. Although there are a few procedures developed for use in subduction earthquake ones (e.g., Urzua and Christian [4] proposed a relation to estimate seismic displacements applicable only for rigid slopes using ground motion recordings from 3 Chilean subduction interface earthquakes), there is a relative lack of robust simplified seismic slope displacement procedures that can be used to evaluate earth systems and slopes in subduction seismotectonic settings. A comprehensive earthquake database of subduction interface earthquakes is first required, and such a database has been developed in this study. It will be used to formulate a model that captures seismic slope displacements of geotechnical structures undergoing subduction interface earthquakes.

2. Database for subduction earthquakes

Bray and Travasarou [1] highlighted the importance using actual earthquake ground motion recordings to develop a robust simplified seismic slope displacement estimation procedure. The uncertainty in the ground motion characterization is the dominant source of uncertainty in calculating seismic slope displacements. Therefore, procedures based on a large number of actual earthquake ground motion recordings are expected to be superior to procedures based on artificial simulated ground motions or those based on a modest number of recorded earthquake ground motions.

In this study, a comprehensive database containing 2244 recorded ground motions from subduction zone inter-plate earthquakes was developed. However, only the ground motion recordings from earthquakes with magnitudes $M \geq 7.0$ (1620 ground motion recordings) are used to generate the seismic displacements data, to avoid any bias from the low magnitude earthquakes that are of less practical interest. Approximately 470 processed earthquake ground motion recordings were obtained from Darragh [5] and PEER [6]. The remaining ground motions were obtained from seismic agencies websites and processed in a uniform manner following the recommendations of the PEER [7] procedure, which is shown in Fig. 1. The ground motion records from the developed database conform to the following criteria (1) $5.8 \leq M_W \leq 9.0$, (2) $R \leq 450$ km (epicentral distance), (3) site class A, B, C or D according to IBC [8] site definitions (for cases in which shear wave velocity values were not available the site class was assigned based on local soil conditions or geological maps in the area of the seismic station), and (4) frequencies in the range of 0.20 – 10Hz have not been filtered out.

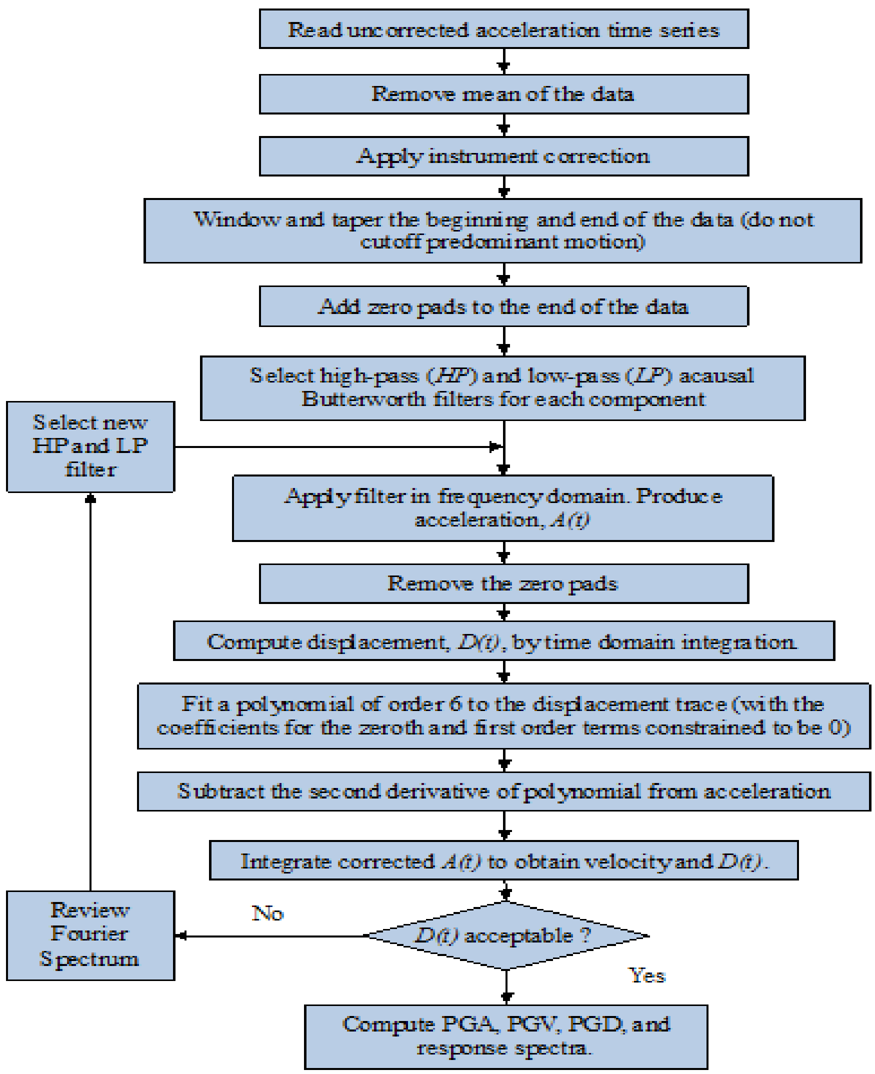

Fig. 1 – PEER record processing procedure. From PEER [7]

Fig. 2 shows the distribution of magnitudes and distances (epicentral distance was used in the plot, however as will be shown later, distance is not used to formulate the predictive equations) of the initial earthquake ground motion database. As discussed previously, only events with magnitudes 7 and greater were used in the final regression. The two horizontal components of each record were used to calculate an average seismic displacement for each side of the records, and the maximum of these values was assigned to that record.

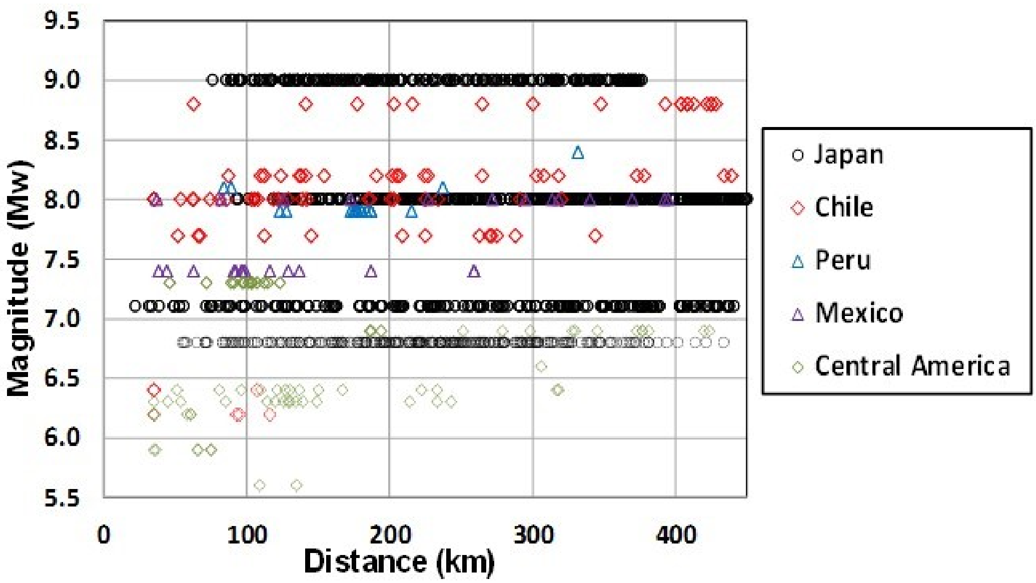

Fig. 2 – Distribution of magnitudes and distances (epicentral) for the compiled subduction (interface) earthquake database.

3. Generation of seismic displacements

This section describes the generation of the calculated seismic displacement data that is used to develop the regression equations for estimating seismic slope displacements.

3.1 Idealized sliding mass model

The nonlinear coupled stick-slip deformable sliding model proposed by Rathje and Bray [9] for one-directional sliding, which is shown in Fig. 3, is used in this study. However, instead of using the Newmark integration method for the integration of the governing equations as recommended by Rathje and Bray [9], the motion equation is solved by a step-by-step analytical solution of the governing equations, following the recommendations by Chopra and Zhang [10]. This procedure has shown to be more stable numerically compared with the solution based on the Newmark method.

The seismic response of the sliding mass is captured by an equivalent-linear viscoelastic modal analysis that uses strain-dependent material properties to approximate the nonlinear response of the earth materials. Comparison of this model with an uncoupled deformable model, rigid block model, fully nonlinear stick-slip deformable model, stick-slip deformable with more than one mode shape model, as well as the model validation against shaking table experiments are described in Rathje and Bray [9], Rathje and Bray [11], Wartman et al. [12], among other studies. The fully coupled, deformable sliding block model has been shown to be appropriate for calculating seismic slope displacements as part of a simplified assessment method.

The model used herein is one dimensional (i.e., a relatively wide vertical column of deformable soil) to allow for the use of a large number ground motions with wide range of properties of the potential sliding mass. As described in Bray and Travasarou [1], 1D analysis can underestimate the seismic demand for shallow sliding at the top of 2D systems where topographic amplification is significant. For this special case, the input PGA can be amplified as recommended by Rathje and Bray [13] for moderately steep slopes (i.e., ~1.3 PGA) and by Ashford and Sitar [14] for steep slopes (i.e., ~1.5 PGA).

Also it is important to emphasize, that the Newmark sliding block mechanism used in the nonlinear coupled stick-slip slope model captures that part of the seismically induced permanent displacement attributed to shear deformation (i.e., either rigid body slippage along a distinct failure surface or distributed shearing within the deformable sliding mass). Ground movement due to volumetric compression is not captured explicitly by Newmark-type models. This is an important distinction of this slope displacement model. Hence, it is preferred to separate shear and volumetric compression effects and use procedures based on the sliding block model to estimate shear-induced displacements and use procedures based on the seismic compression of soils (e.g., Tokimatsu and Seed [15]) to estimate volumetric-induced displacements. The calculated shear-induced ground displacement and volumetric-induced ground displacement should then be combined to develop the total estimate of seismically induced ground displacement.

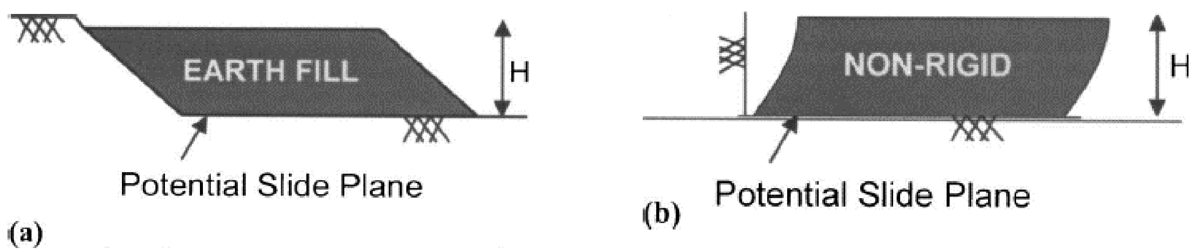

Fig. 3 a) Generic seismic slope displacement problem of height H and initial stiffness V_s, and b) idealized nonlinear coupled stick-slip deformable sliding mass model with one-way sliding used in study (from Bray and Travasarou [1]).

In this study, the sliding mass was assigned a constant unit weight of 19 kN/m^3, the strain-dependent shear modulus reduction and material damping ratio curves correspond to those proposed by Darendeli [16] for 1 atm and PI = 15. Sensitivity analyses indicate that reasonable adjustments of these parameters do not have a significant effect on the computed displacements. The nonlinear coupled stick-slip deformable sliding model being used can be characterized by: (1) its strength as represented by its yield coefficient (k_y), and (2) its dynamic stiffness as represented by its initial fundamental period (T_s). Seismic displacement values were generated by computing the response of the idealized sliding mass model with specified values of its yield coefficient (i.e., k_y=0.01,0.02,0.035,0.05, 0.075, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, and 0.8) and its initial fundamental period (i.e., T_s=0, 0.05,0.1,0.2, 0.3, 0.5, 0.7, 1.0, 1.4, and 2.0 s) to the entire set of recorded earthquake motions described previously. For the baseline case, the overburden-stress corrected shear wave velocity (V_{S1}) was set to 270 m/ s, and the shear wave velocity profile of the sliding block was developed using the relationship that shear wave velocity (V_S) is proportional to the fourth-root of the vertical effective stress. The sliding block height (H) was increased until the specified value of T_S was obtained. For common T_S values from 0.1 to 0.7 s, another reasonable combination of H and average V_S were used to confirm that the results were not significantly sensitive to these parameters individually. For nonzero T_S values, H varied between 3 and 100 m, and the average V_S was between 200 and 450 m/ s. All sliding block systems would be classified as 2013 International Building Code Sites C or D. Hence, realistic values of the initial fundamental period and yield coefficient for a wide range of earth/rockfill dam, natural slope, heap leach pads, and solid-waste landfill were used.

3.2 Distribution of seismic displacement

The seismic displacements (>1 cm) calculated for the set of idealized slopes defined previously, each with its specific yield coefficient and initial fundamental period, undergoing the 1620 earthquake ground motions described previously are shown in Fig. 4. The variation of the calculated seismic displacement is plotted against the slope yield coefficient, the slope's initial fundamental period, earthquake magnitude, and the ground motion's spectral acceleration at 1.5 times the slope's initial fundamental period. The scatter in these graphs is significant. However, examining the trends of the data, seismic displacement generally decreases with increasing yield coefficient as expected, there is a modest sensitivity of seismic displacement to the slope's fundamental period, and seismic displacements tend to increase with increasing earthquake magnitude. Also, the amount of calculated seismic displacement is correlated to the spectral acceleration of the input earthquake ground motion at the degraded period of the slope, taken as 1.5 times the initial fundamental period with displacement increasing significantly as $S_a(1.5T_s)$ increases. The results shown in Fig. 4 and the calculated seismic displacement values that are less than 1 cm are the "simulated data" used to develop the regression equations for estimating seismic displacements.

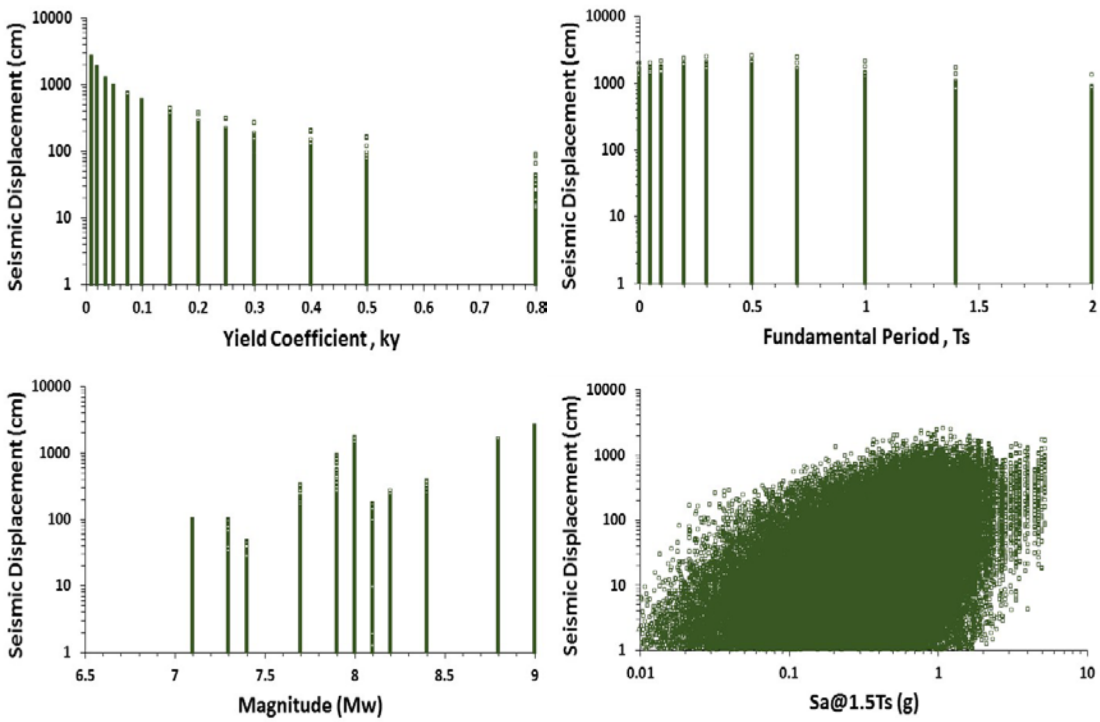

Fig. 4 – Distribution of simulated displacement data for D> 1 cm with yield coefficient k_y, initial fundamental period T_S, moment magnitude, and spectral acceleration at 1.5 times the initial fundamental period

4. Model for estimating seismic shear-induced slope displacements

4.1 Functional form

As discussed in Bray and Travasarou [1], seismically induced permanent displacements can be modeled as a mixed random variable, which has a certain probability mass at zero displacement and a probability density for finite displacement values. Displacements smaller than 1 cm are not of engineering significance and can for all practical purposes be considered as negligible or "zero." Additionally, the regression of displacement as a function of a ground motion intensity measure should not be dictated by data at negligible levels of seismic displacement. Then the values of seismic displacements that are smaller than 1cm are lumped together to d_0=1cm. Consequently, the probability density function of seismic displacements can be described as:

$$f_D(d) = \bar{P}\delta(d - d_0) + (1 - \bar{P})\bar{f}_D(d) \tag{1}$$

Where $f_D(d)$ is the displacement probability density function; $\bar{P}$ is the probability mass at D = d_0; $\delta(d - d_0)$ is the Dirac delta function and $\bar{f}_D(d)$ is the displacement probability density function for D > d_0. Fig.

5 shows the case of a mixed probability distribution with a finite probability at D= d_0 and continuous probability density for D > d_0. As shown in Fig. 5, the probability of exceedance at small displacements can be smaller than 1 implying the possibility of having "zero" (i.e., < 1cm) displacements.

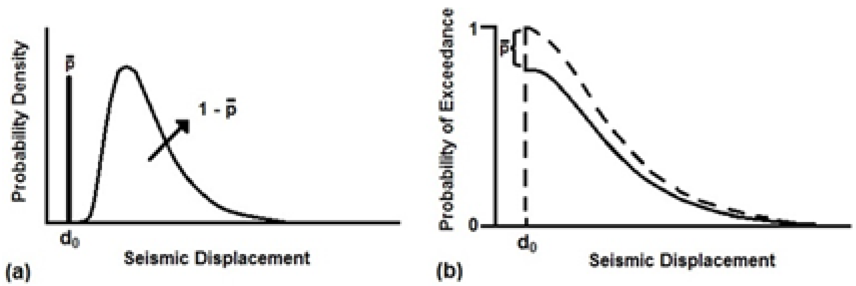

Fig. 5 – a) Probability density function for a mixed random variable and b) probability of exceedance for a mixed and a continuous random variable

Following the concept of a mixed random variable, first the probability of "zero" (i.e. D≤1 cm) displacement needs to be defined in terms of the primary independent variables which, as discussed previously, are k_y and T_S representing the physical properties of the geotechnical system and $S_a(1.5T_s)$ representing the ground motion excitation.

Based on the simulated displacement data, the dependence of the probability of zero displacement on the three independent variables is illustrated in Fig. 6. The probability of "zero" displacements decreases significantly as the ground motion's spectral acceleration at the degraded period increases and increases significantly as the yield coefficient increases. In regard to the slope's fundamental period, the probability of "zero" displacement decreases initially as the fundamental period increases from zero, since the slope is being brought to a resonance condition. For continuing increasing values of the slope's fundamental period the probability of "zero" displacement increases as the slope moves away from the resonance condition. Similar trends were obtained in the study of Bray and Travasarou [1] for shallow crustal earthquakes along active plate margins.

The trends shown in Fig.6 have guided the selection of the functional form for the predictive equation for the probability of "zero" displacement. A probit regression analysis (Green [17) was employed to calculate the coefficients of the predictive equation for the probability of "zero" displacement. Compatible with the concept of a mixed random variable, given that a finite probability of "nonzero" displacement is calculated, the amount of nonzero displacement needs to be estimated. The distribution of seismic displacement is computed, given that nonzero displacement has occurred. A truncated regression (Green [17]) along with the principle of maximum likelihood was employed to calculate the coefficients of the predictive equation for "nonzero" displacement.

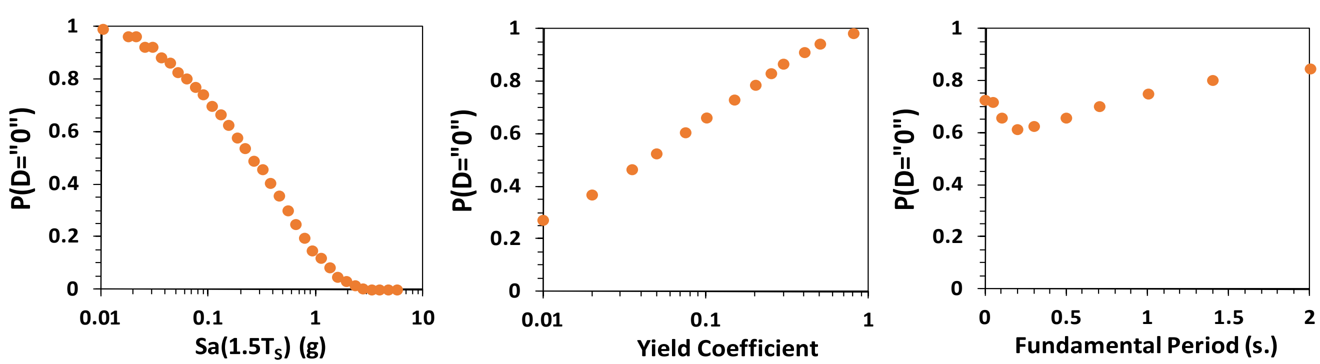

Fig. 6 – Dependence of the probability of zero displacement on the spectral acceleration at 1.5 times the initial fundamental period, yield coefficient; and initial fundamental period

4.2 Simplified model for estimating seismic slope displacements

The model for estimating seismic slope displacements consists in two computation steps: (1) the probability of "zero" (i.e. D $\leq$ 1 cm) displacements, and 2) the likely amount of "nonzero" displacement. The model for computing the probability of "zero" displacement is:

For $Ts \leq 0.7$ sec.

$$P(D=0) = 1 - \Phi\left(-2.75 - 3.3Ln(k_y) - 0.18\left(Ln(k_y)\right)^2 - 0.56TsLn(k_y) + 1.94T_s + 2.95Ln(Sa(1.5T_s))\right) \quad (2)$$

For $Ts > 0.7$ sec.

$$P(D=0) = 1 - \Phi\left(-3.77 - 5.17Ln(k_y) - 0.40\left(Ln(k_y)\right)^2 - 0.43TsLn(k_y) - 1.03T_s + 2.91Ln(Sa(1.5T_s))\right) \quad (3)$$

Where $P(D=0)$ is the probability of occurrence of zero displacement (as a decimal number); D is the seismic displacement; Φ is the standard normal cumulative distribution; k_y is the yield coefficient; T_s is the fundamental period of the sliding mass in seconds; and $Sa(1.5T_s)$ is the spectral acceleration at a period of $1.5T_s$ in the units of g of design outcropping ground motion for the site conditions below the potential sliding mass (i.e., the ground motion intensity at the site if the potential sliding mass was removed).

Some comparisons of the model estimates versus the simulated data and the Bray and Travasarou [1] model (BT07) are shown in Fig.7. The model separates the calculation of probability of "zero" displacements for systems with low and moderately high periods (i.e.. $T_s \leq 0.7$ sec.) from those with high periods (i.e.. $T_s > 0.7$ sec.). This allows to better capture the probability of "zero" displacement for systems with large fundamental initial period.

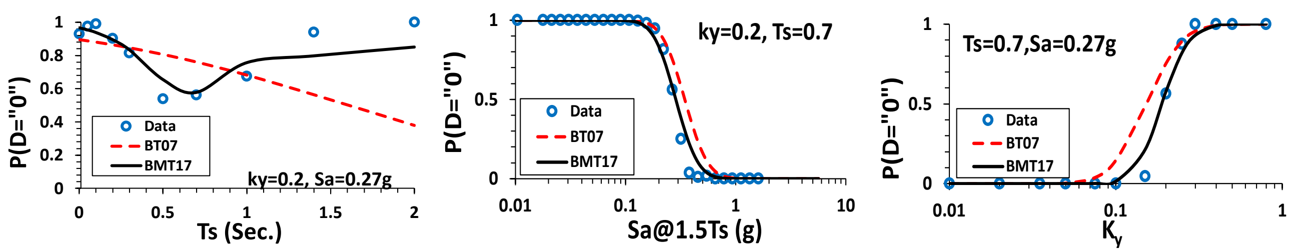

Fig. 7 – Comparison of predicted probability of zero displacement i.e., D$\leq$ 1 cm for the model developed in this study (BMT17) versus the simulated displacement data from subduction zone events considered in this study and the BT07 model originally developed for shallow crustal earthquakes in active tectonic margins.

The amount of the nonzero displacement (D) in centimeters is estimated as:

$$Ln(D) = -6.97 - 3.045Ln(k_y) - 0.328\left(Ln(k_y)\right)^2 + 0.448Ln(k_y)Ln(Sa(1.5T_s)) + 2.605Ln(Sa(1.5T_s)) - 0.233\left(Ln(Sa(1.5T_s))\right)^2 + 1.407T_s + 0.643M \pm \varepsilon \quad (4)$$

where k_y, T_s, $Sa(1.5T_s)$ are as defined previously for Eq. (3) and ε is a normally distributed random variable with zero mean and standard deviation σ=0.73. To eliminate a bias in the model when T_s~0 the first term of Eq. (4) should be replaced with -6.37 when T_s<0.05. This cases of T_s~0 corresponds to the Newmark rigid sliding block case. In that case, the amount of nonzero displacement (cm) is estimated as:

$$Ln(D) = -6.37 - 3.045Ln(k_y) - 0.328\left(Ln(k_y)\right)^2 + 0.448Ln(k_y)Ln(PGA) + 2.605Ln(PGA) - 0.233\left(Ln(PGA)\right)^2 + 1.407T_s + 0.643M \pm \varepsilon \tag{5}$$

where PGA is the peak ground acceleration of the ground motion. The rigid body case (i.e., T_s~0) can be important for shallow slides. If there are important topographic effects to capture for localized shallow sliding, the design PGA value should be adjusted accordingly (i.e., $1.3PGA_{1D}$ for moderately steep slopes, e.g., 2H:1V, or $1.5PGA_{1D}$ for steep slopes, e.g., 1H:2V). For long, shallow potential sliding masses, lateral incoherence of ground shaking would reduce the design PGA value employed in the analysis (e.g., Rathje and Bray [13]).

The residuals (i.e., $Ln(D_{data})$ - $Ln(D_{Predicted})$) of Eq. (4) and (5) are plotted in Fig. 8 in terms of the yield coefficient and the magnitude and in Fig. 10 in terms of the fundamental period (the BMT16 model correspond to this study). The residuals shown in Fig. 8 are significant, but this is due to the inherent variability of estimating seismic displacement. The residuals versus yield coefficient and magnitude show almost no bias. There is only a slight bias with respect to the fundamental period, which is not significant and with compensating effects (for example for the range of low to moderate high periods, i.e. from 0 to 0.7 sec., a slightly negative residual for T_s. ≤0.35 sec. and a slightly positive residual for 0.35< T_s. ≤0.70).

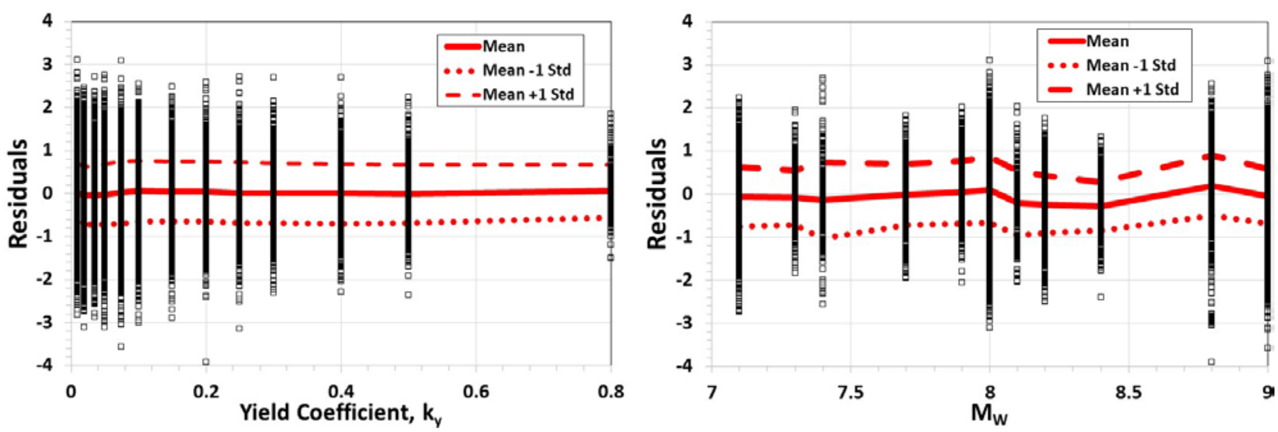

Fig. 8 – Residuals ($Ln(D_{data})$ – $Ln(D_{Predicted})$) of Eq. (4) and Eq. (5) plotted versus yield coefficient, the initial fundamental period, and the magnitude

The proposed methodology can also be used to calculate the probability of the seismic displacement exceeding a selected threshold of displacement (d) for a specified earthquake scenario (i.e. M, $Sa(1.5T_s)$), and slope properties (i.e. k_y, T_s). The probability of the seismic displacement (D) exceeding a specified displacement threshold (d) can be calculated as:

$$P(D > d) = [1 - P(D = 0)]P(D > d/D > 0) \tag{6}$$

$P(D = 0)$ is computed using Eq. (2) and Eq. (3). The term $P(D > d/D > 0)$ may be computed assuming that the estimated displacements are lognormally distributed as:

$$P(D > d/D > 0) = 1 - P(D \leq d/D > 0) = 1 - \Phi\left(\frac{Ln(d) - Ln(\tilde{d})}{\sigma}\right) \tag{7}$$

where $Ln(\tilde{d})$ is calculated using Eq. (4) or (5), σ is the standard deviation of the random error equal to 0.73, and Φ is the standard normal cumulative distribution function.

The trends for the proposed model are shown in Fig.9. The upper plots show trends for a M_W =9.0 interface subduction earthquake at a distance of 35 km (this distance is in the closest range of distances to an interface seismic source but could be a realistic scenario for some projects, e.g., South America coast, and is used only for illustrative purposes) The probability of negligible seismic displacements and the estimation of the seismic displacement depend significantly on yield coefficient and the initial fundamental period of the slope. The influence of the initial fundamental period is more significant for systems with high yield coefficients. The first two lower plots are for a M_W =9.0 interface earthquake at several distances from the site so that the ground motion intensity parameters PGA and Sa(1.5T_S) vary significantly for the case of a rigid sliding block or a deformable sliding block with initial fundamental period of 0.3 sec. Finally, the partial effect of earthquake magnitude at a particular level of ground motion intensity (i.e. Sa(0.45s s)=0.8g) is shown in the last lower figure. It is a partial effect, because the estimated value of spectral acceleration typically increases with increasing earthquake magnitude, which increases seismic displacement. This effect is not shown in this figure, because spectral acceleration was held constant.

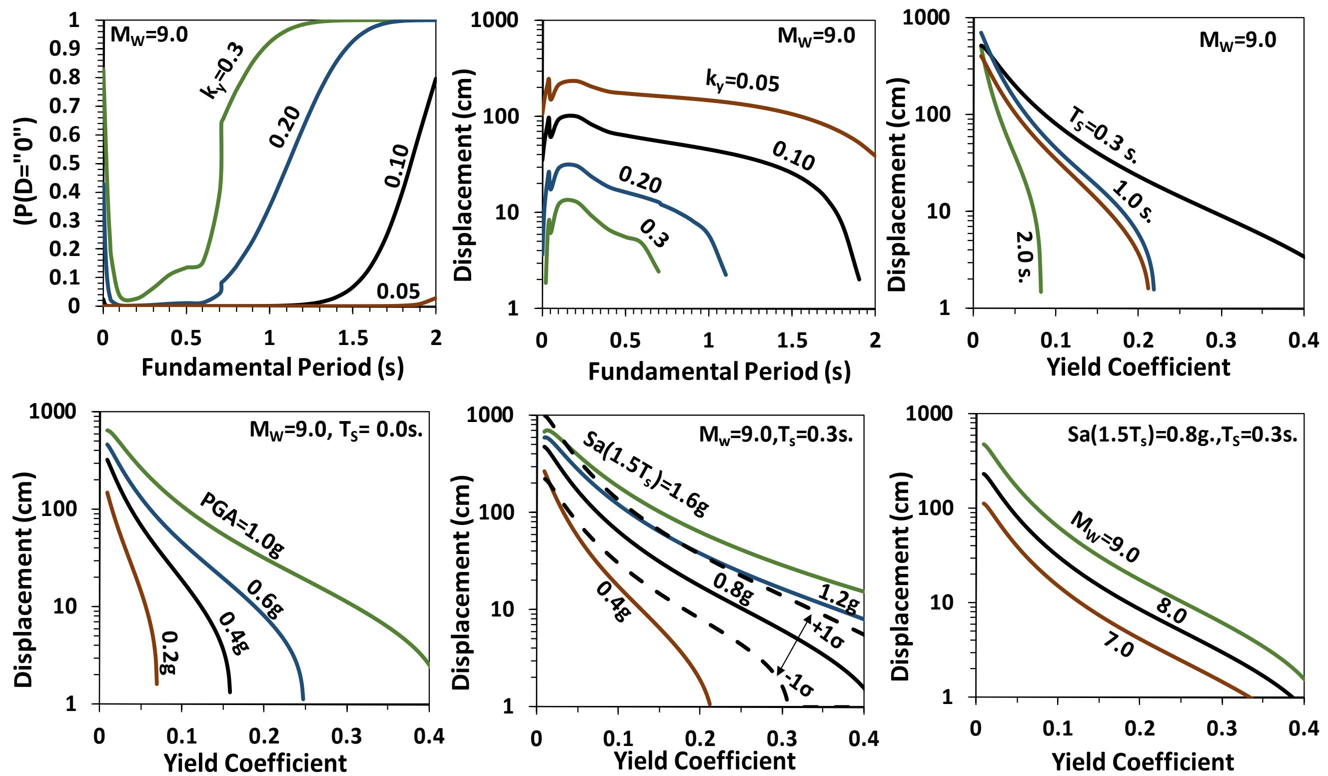

Fig. 9 – Model trends: a) upper figures show the dependence of the probability of "zero" seismic displacement and seismic displacements for a M_W 9.0 interface earthquake at a distance of 35 km with respect to yield coefficient and initial fundamental period, and b) lower figures show the dependence of the median calculated seismic displacements with respect to the system yield coefficient and ground motion intensity parameters at several distances. Also shown is the dependence respect to magnitude for Sa(0.45s) = 0.8g)

4.3 Comparison of the proposed seismic slope displacement model for subduction earthquakes and the BT07 shallow crustal earthquake-based model

This study uses the framework of the Bray and Travasarou [1] simplified method (BT07), while incorporating several improvements that have been discussed in previous sections. The BT07 was originally developed for shallow crustal earthquakes. Hence, comparisons are presented in this section with reference to this method.

Fig. 10 shows the residuals obtained by applying the BT07 model to the simulated data in this study. In terms of the yield coefficient, the residuals using the BT07 method are more negative compared to the residuals using the equations derived in this study for subduction zone earthquakes (i.e., Eq. (4) and Eq. (5)), which implies that use of the BT07 method is conservative if used in subduction settings. However, notice also that the mean residuals using BT07, for the more common values of yield coefficient found in practice (i.e., k_y <0.3) are close to zero indicating that the BT07 method is not significantly biased in the practical range of k_y values. The residuals of BT07 model vs. the simulated subduction zone earthquake data are slightly more negative compared with the residuals derived in this study for the range of periods from 0.0 sec. to approximately 0.50 sec.. However, the BT07 method is not significantly biased. This conservatism of BT07 method also appears when plotting the residuals in terms of the earthquake magnitudes (the plot is not showed). The residuals using BT07 method are more negative than the residuals derived in this study, decreasing (getting less negative) as the magnitude increases, and tending to zero for large magnitudes.

The differences between the BT07 method and the proposed method for subduction zone earthquakes result from two key factors. Firstly, the extrapolation of the BT07 model for ranges of values not considered in its development is marginal at times (e.g., the BT07 study considered a maximum k_y of 0.4, and the residuals compared with the method developed in this study increase with larger k_y values). Secondly, the characteristics of the databases considered for the analysis differ. This study considered 1620 ground motion records from interface subduction earthquakes whereas the BT07 model was developed using 688 ground motion records from shallow crustal earthquakes along an active plate margin. Consequently, the proposed model is based on a broader range of distances and magnitudes. As expected, there are differences attributed to the unique characteristics of ground motions from shallow crustal and subduction settings. For example, it has been observed empirically, for a given earthquake magnitude, that the ground motion records from shallow crustal settings tend to have a stronger long period content energy compared with ground motion records from subduction interface settings (i.e., in terms of spectral shape, spectral accelerations tend to drop at a slower rate for long periods). This effects is captured by ground motion prediction equations (GMPE) proposed for these seismic settings (e.g., Abrahamson, Silva and Kamai [18] and Abrahamson, Gregor and Addo[19]), as illustrated in Fig.11. Because the amount of seismic slope displacements is governed more by long period energy, the negative (conservative) residuals of the BT07 method (when used in subduction settings) is consistent with the described empirical observations and GMPEs.

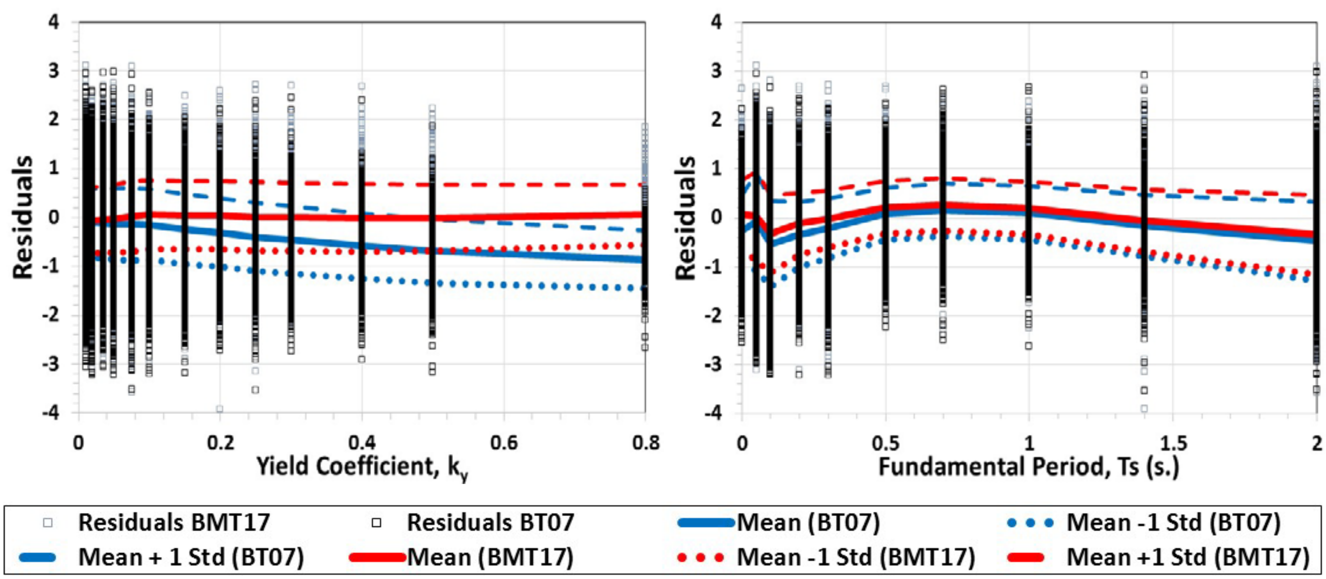

Fig. 10 – Comparison of residuals (i.e. $Ln(D_{data})$ $-Ln(D_{Predicted})$) from the BT07 method versus the proposed BMT17 equations for use in subduction earthquake zones

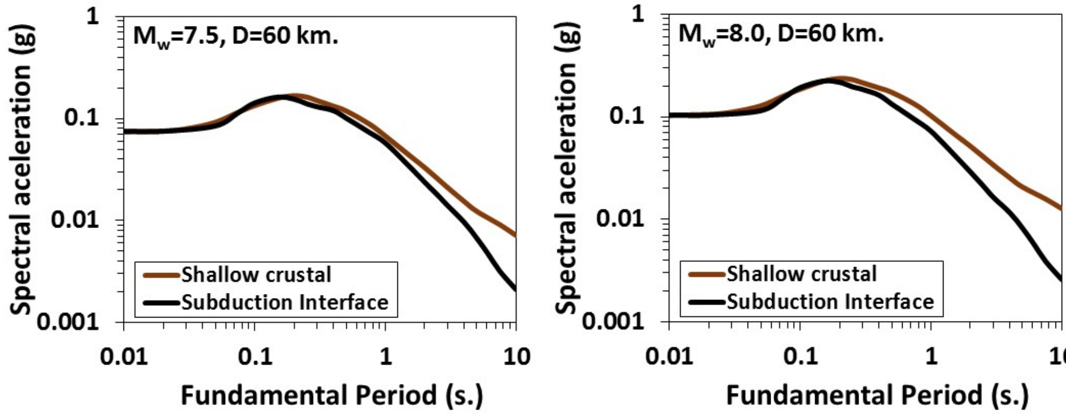

Fig. 11 – Spectral shape comparison shallow crustal and subduction interface response spectra using [18] and [19]. PGA is normalized to the value corresponding to the shallow crustal response spectrum

Another difference to highlight between the BT07 method and the method proposed in this study, associated with particularities between shallow crustal and subduction settings, is the difference between the magnitude scaling terms in both methods. The magnitude scaling term for the BT07 method and the proposed method for subduction settings are 0.278 and 0.643, respectively. The greater magnitude scaling terms for subduction settings is also consistent with what has been observed for ground motion prediction equations for spectral accelerations - which are correlated with seismic displacements (e.g., [18] and [19]). Interestingly, the BT07 method provides reasonably conservative estimates of the calculated seismic slope displacement when applied to subduction settings. However, the proposed seismic slope displacement procedure better captures the unique seismic setting of subduction zone earthquakes. Hence, it should be used to estimate seismic slope displacements for interface subduction earthquakes.

5. Conclusions

A simplified procedure was developed for estimating seismic slope displacements for subduction zone interface earthquakes. The seismic displacement data used in the model development were created using a Newmark-type nonlinear soil response, fully coupled stick-slip sliding block analysis of numerous cases with a wide range of k_y and T_s values. Importantly, the seismic displacement analyses were performed using a comprehensive database of 1620 pairs of horizontal components of uniformly processed ground motions recorded during subduction zone interface earthquakes worldwide. The primary source of uncertainty in assessing the likely performance of an earth/waste system during an earthquake is the input ground motion, so the proposed model takes advantage of the wealth of strong motion records for subduction settings that have become available recently.

A comparison of the proposed procedure with the Bray and Travasarou [1] procedure (BT07), which was developed for shallow crustal earthquake settings, shows that the BT07 procedure is reasonably conservative (in terms of residuals) when it is used to estimate seismic slope displacements for subduction zone interface earthquakes. There are differences between the ground motion recordings of subduction zone earthquakes and shallow crustal earthquakes. However, the differences are not as significant as might have been conjectured. Considering that the amount of seismic displacement is most influenced by the long period energy, it is consistent with empirical observations that for a given earthquake magnitude, the ground motion records from shallow crustal settings tend to have a stronger long period content energy compared with ground motion records from subduction interface settings. Also, the magnitude scaling term of the proposed model is lesser than the magnitude scaling term of theBT07 model, and this is in agreement with similar differences that have been observed for ground motion prediction equations in shallow crustal and subduction settings ([18], [19]). The proposed seismic slope displacement model better captures the unique seismic setting of subduction zone interface earthquakes. Hence, it should be used to estimate seismic slope displacements for these types of events.

The seismic displacement model depends significantly on the spectral acceleration of the design outcropping ground motion for the site below the sliding mass at a degraded period of the potential sliding mass (i.e. $Sa(1.5T_s)$). The system's seismic resistance is best captured by its yield coefficient (k_y), but the dynamic response characteristics of the potential sliding mass are also an important influence, which can be captured by its initial fundamental period (T_s). This model only attempts to capture the mechanisms that are consistent with the Newmark method (i.e., shear-induced displacement due to sliding on a distinct plane and distributed shearing within the slide mass). Thus, if volumetric compression seismic displacements are likely to be significant, they have to be calculated separately with an appropriate analysis.

The proposed model considers a mixed random variable for displacements so that very low values of calculated displacement (i.e. $\leq$ 1 cm.) that are not of engineering interest do not bias the results. In this procedure, the probability of "zero" displacement occurring is first calculated using Eq. (2) and Eq. (3). Then the amount of "nonzero" displacement is estimated from Eq. (4) and (5). The 16 and 84% exceedance seismic displacement values may be computed using Eq. (6) and Eq. (7) by solving for the displacement value d that gives $P(D> d) =0.16$ and 0.84, respectively. The proposed model can be implemented rigorously within a fully probabilistic framework for the evaluation of the seismic displacement hazard, or it may be used in a deterministic analysis. In all cases, however, the estimated range of seismic displacement should be considered merely an index of the expected seismic performance of the earth system.

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