Karamitros, D., Nicolaidou, E., & Alexander, N. (2018). Seismic settlements of shallow foundations: a sliding block approach. In *Recent Advances in Earthquake Engineering in Europe: Proceedings of the 16th European Conference on Earthquake Engineering (16ECEE)* European Association for Earthquake Engineering (EAEE).

16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING THESSALONIKI 18 - 21 JUNE 2018

SEISMIC SETTLEMENTS OF SHALLOW FOUNDATIONS: A SLIDING BLOCK APPROACH

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ABSTRACT

Allowing the seismic bearing capacity of shallow foundations to be momentarily exceeded during extreme earthquake events can function as a mechanism of natural seismic isolation that is beneficial for the superstructure. However, this effect comes at the price of accumulating foundation settlements, which also need to be accounted for in the performance-based design process. Although the seismic bearing capacity of footings can be estimated with reasonable accuracy, there is still no widely approved methodology to calculate the associated seismic settlements. This paper attempts to address this issue through an extension of Newmark's sliding block analysis, where the footing is modeled as a rigid block on a horizontal surface, with the block-base friction being a function of the critical seismic acceleration to trigger bearing capacity failure. When the block is subjected to an earthquake excitation and the frictional resistance is exceeded, an accumulating vertical displacement is also calculated, proportional to the amount of horizontal sliding. In the case of symmetric motions, this occurs twice per cycle and vertical settlements accumulate even when the residual horizontal displacement is zero. For quick applications, a semi-analytical factor is derived, correlating the settlements predicted by the proposed model to the residual horizontal displacements of a conventional rigid block sliding on an inclined plane, under the same input motion and with the same critical acceleration. This factor can be used in combination with well-established empirical relations for seismic displacements of slopes and retaining walls, thus extending their applicability to cover the response of shallow foundations.

Keywords: shallow foundations; seismic settlements; sliding block; performance-based design

1. INTRODUCTION

Recent research (e.g. Gazetas, 2015) has clearly demonstrated that controlled "under-design" of shallow foundations to allow bearing capacity mobilization during extreme seismic events can prove beneficial for the superstructure. This is because the development of plastic strains within the foundation subsoil would limit the accelerations transmitted to the structure, hence forming a natural mechanism of seismic isolation. However, the development of a bearing capacity failure mechanism, although momentary, is also accompanied by settlement of the foundation. This settlement accumulates during the seismic event, resulting in a residual displacement that should remain within allowable limits. As a result, incorporation of this natural seismic isolation concept into performance-based design applications requires (a) the accurate estimation of the seismic bearing capacity of the footing and (b) the evaluation of the residual settlements that would accumulate during the design earthquake, when this bearing capacity is exceeded.

The seismic bearing capacity of shallow foundations has been extensively studied during the previous years, using different approaches. For instance, Richards et al. (1993) assumed the formation of active and passive wedges within the foundation subsoil and used a Mononobe-Okabe analysis to derive

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seismic bearing capacity factors, Sarma & Iossifelis (1990), Budhu & Al-Karni (1993), Zhu (2000) and Choudhury & Subba Rao (2005) estimated seismic bearing capacity using the limit equilibrium method, Kumar & Mohan Rao (2002) and Cascone & Casablanca (2016) employed the method of characteristics, while Dormieux & Pecker (1995), Paolucci & Pecker (1997a, 1997b), Soubra (1999) and Chatzigogos et al. (2007) followed a kinematic approach. These studies have been complemented by a series of experimental results, including Maugeri et al. (2000), Gajan et al. (2005) and Knappett et al. (2006).

However, there is still no widely used methodology to calculate the foundation settlements that are expected to accumulate during seismic loading. Most research efforts, including the work of Paolucci (1997), Cremer et al. (2002) and Chatzigogos et al. (2011) have concentrated on extending the applicability of the macro-element modelling technique, originally developed by Nova & Montrasio (1991) for static loading, to also cover the case of dynamic loads. Although these models have been shown to accurately predict seismic settlement accumulation, they involve advanced constitutive formulations that require significant expertise to implement, hence their use in everyday engineering practice remains limited.

This paper attempts to bridge this gap, using a simplified procedure to estimate settlements via a Newmark-type sliding block approach. This technique has been successfully employed to predict the residual displacements of slopes and retaining structures subjected to seismic motions, where the input acceleration momentarily exceeds the "critical acceleration" to mobilize failure. Parametric application of this method for different excitation records has resulted in a series of deterministic and probabilistic relations, as well as design graphs that correlate the residual displacement to the critical acceleration a_{cr}, the maximum input acceleration a_{max}, the peak input velocity v_{max}, the number of cycles N and/or the predominant period T of the excitation. These studies include the works of Makdisi & Seed (1978), Whitman & Liao (1985), Ambraseys & Menu (1988), Yegian et al. (1991), Bray & Travasarou (2007), Voyagaki et al. (2012) and Rathje et al. (2014).

The sliding block methodology is extended herein to simulate the problem of seismic settlement accumulation. Following a description of the involved assumptions and a presentation of the governing differential equations, the proposed model is initially applied for harmonic excitations and then for a total of 105 earthquake records, obtained from the web-based PEER Ground Motion Database. Comparison of the results obtained from the proposed model, against the predictions of conventional sliding block analyses (i.e. for slopes or retaining walls), allows to derive a semi-analytical correction factor, which can be then used in combination with any of the aforementioned empirical relationships for permanent ground displacements, in order to estimate seismic settlements as a function of the critical acceleration a_{cr} and seismic design parameters.

2. METHODOLOGY OUTLINE

2.1 Sliding block approach for seismic settlements

The idea of employing the sliding block model to estimate seismic settlement accumulation originates from the work of Richards et al. (1993). According to this approach, the critical horizontal acceleration a_{cr} to mobilize seismic bearing capacity failure needs to be initially estimated. To achieve this, Richards et al. (1993) assume the formation of active and passive wedges within the foundation subsoil (Figure 1). Taking the effects of earthquake acceleration into account, these wedges are analyzed with the Mononobe-Okabe method to obtain the seismic bearing capacity. The critical acceleration a_{cr} is then calculated as the earthquake acceleration for which the factor of safety against bearing capacity failure becomes equal to $FS_{seismic}$=1.

It is noted that the bearing capacity factors proposed by Richards et al. (1993) have been criticized by other researchers, including the discussion by Dormieux & Pecker (1995). This debate involves the effect of soil inertia forces and how important this is as compared to the effect of load eccentricity and inclination. However, the analysis presented herein draws upon the sliding block approach proposed by Richards et al. (1993) and not on their methodology to estimate seismic bearing capacity. The critical acceleration used for the sliding block analysis can be estimated using any seismic bearing capacity factors by simply imposing the requirement of $FS_{seismic}$=1. For a rigorous analysis, these factors should account for both the seismic horizontal loads and overturning moments.

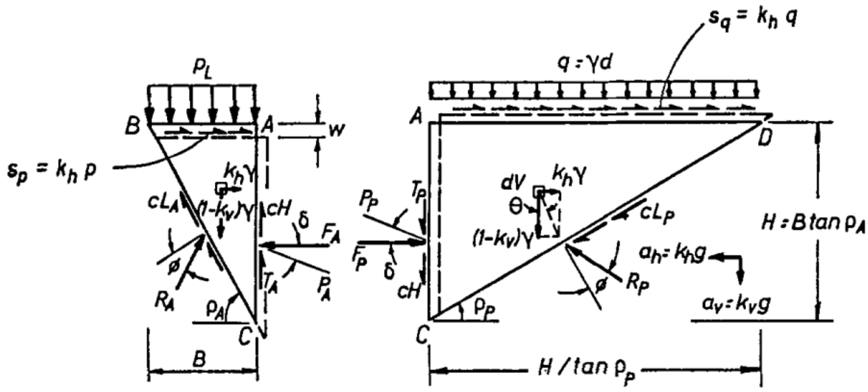

Figure 1. Bearing capacity failure mechanism after Richards et al. (1993).

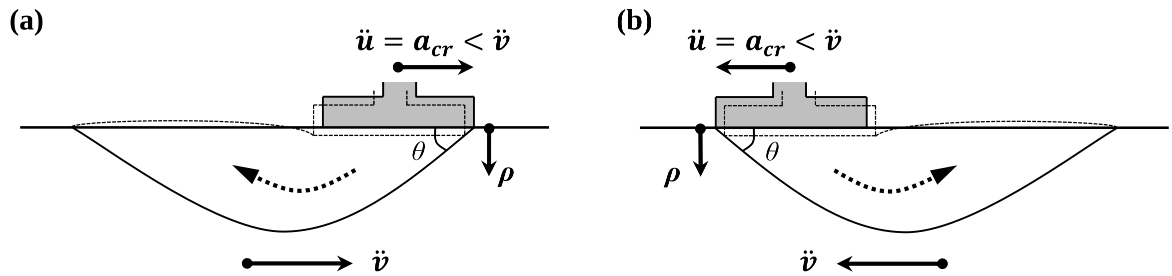

Figure 2. (a,b) Schematic representation of the mobilized failure mechanisms

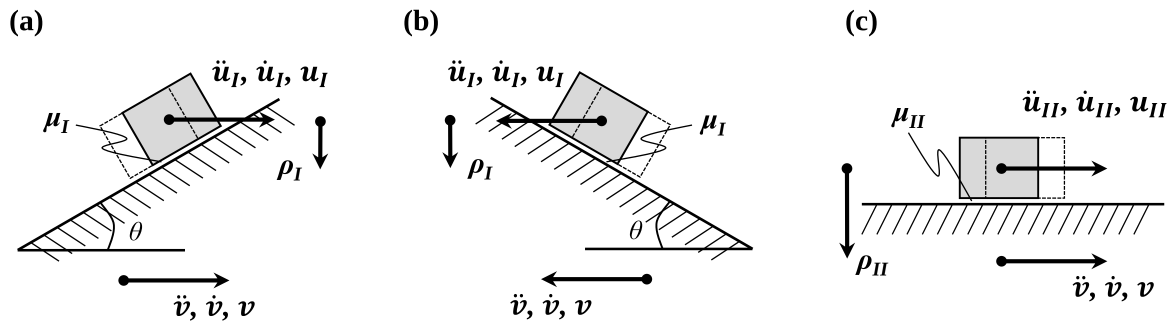

Figure 3. Analogues (a,b) of alternating sliding blocks on inclined planes & (c) of block on horizontal surface.

According to the sliding block approach proposed by Richards et al. (1993), when the input acceleration $\ddot{v}$ is pointing to the right and its value exceeds the critical acceleration a_{cr}, bearing capacity is mobilized (Figure 2a) and the footing accelerates to the right with a smaller horizontal acceleration of $\ddot{u} = a_{cr} < \ddot{v}$. This corresponds to "sliding" towards the left, accompanied by a vertical settlement. Similarly, when a leftward input acceleration exceeds the critical value, the footing "slides" to the right and settles (Figure 2b). It becomes obvious that after a series of rather symmetrical cycles, the residual horizontal displacement would be close to zero. However, vertical displacement would accumulate twice per cycle, resulting in substantial residual settlement.

2.2 Model I: Conventional sliding block on inclined plane

The mechanical analogue suggested by Richards et al. (1993) to capture the aforementioned behavior includes the two alternating sliding block models shown in Figures 3a and 3b (hereafter denoted Model I). According to their analysis, the slope angle θ represents the ratio between horizontal displacement u_I and vertical settlement ρ_I, as shown in Figure 2. In order for sliding to occur when the critical acceleration a_{cr} is exceeded, the friction coefficient μ_I between the block and the inclined plane is calculated as:

$$\mu_I = \frac{a_{cr}/g + \tan\theta}{1 + a_{cr}\tan\theta/g} \tag{1}$$

Richards et al. (1993) assumed that since the two models of Figures 3a and 3b are symmetric, only one of them needs to be considered, hence reducing the problem to the conventional model of a "sliding block on an inclined plane", similar to the one employed for slopes and retaining walls.

Accounting only for downslope sliding (upwards movements would not be applicable in the case of shallow foundations examined herein), the differential equation governing the response of the block can be expressed as:

$$\ddot{u}_I(t) = \begin{cases} \ddot{v}(t) \;, & \ddot{v}(t) < a_{cr} \quad and \quad \dot{v}(t) = \dot{u}_I(t) \\ a_{cr} \;, & otherwise \end{cases} \tag{2}$$

where $u_I, \dot{u}_I, \ddot{u}_I$ and $v, \dot{v}, \ddot{v}$ are the horizontal displacement, velocity and acceleration of the block and base, respectively. The vertically accumulating seismic settlement can be then defined as a function of the horizontal movement of the block, as:

$$\rho_I(t) = 2 \cdot u_I(t) \cdot \tan\theta \tag{3}$$

where the factor of 2 accounts for the two alternating sliding mechanisms (Figures 3a and 3b).

The above analysis by Richards et al. (1993) is very convenient, as it implies that seismic settlements can be readily estimated via a conventional inclined-base sliding-block analysis, simply by multiplying the resulting residual horizontal displacements by a factor of 2·tanθ. This factor could also be used in combination with any of the existing relationships available in the literature (e.g. Makdisi & Seed, 1978, Whitman & Liao, 1985, Ambraseys & Menu, 1988, Yegian et al, 1991, etc), hence rendering their methodology readily applicable to engineering practice. For instance, Richards et al. (1993) suggest that their own empirical equation for the seismic displacements of retaining walls (expression in brackets, in Equation 4) can be extended to cover the case of seismic settlements of foundations, as:

$$\rho_{I,total} = 2 \cdot \left[0.087 \cdot \frac{v_{\max}^{2}}{a_{\max}} \left(\frac{a_{cr}}{a_{\max}} \right)^{-4} \right] \cdot \tan\theta \tag{4}$$

where a_{max} and v_{max} are the peak acceleration and peak velocity of the design earthquake.

2.3 Model II: Proposed sliding block on horizontal plane

The validity of the mechanical analogue and the resulting correction factor proposed by Richards et al. (1993) has not been examined in the literature. In this paper, the model of Richards et al. is compared against the more appropriate analogue of a rigid block on a horizontal surface (Figure 3c, hereafter called Model II), with a block-base friction coefficient of:

$$\mu_{II} = \frac{a_{cr}}{g} \tag{5}$$

Denoting the horizontal displacement, velocity and acceleration of the block and base as $u_{II}, \dot{u}_{II}, \ddot{u}_{II}$ and $v, \dot{v}, \ddot{v}$ respectively, the motion of the block in Model II can be described using the following differential equation:

$$\ddot{u}_{II}(t)=\begin{cases}\ddot{v}(t) & , \quad |\ddot{v}(t)|<a_{cr} \quad and \quad \dot{v}(t)=\dot{u}_{II}(t) \\ \mathrm{sgn}\left[\dot{v}(t)-\dot{u}_{II}(t)\right]\cdot a_{cr} & , \quad otherwise\end{cases} \tag{6}$$

Obviously, this analogue has the advantage of simulating the footing's response and sliding towards both directions using only one set of equations, without the need of alternating inclined-plane models. However, it does not effectively allow to visualize seismic settlements. Still, settlement can be assumed to accumulate when sliding occurs towards any direction and it can be therefore calculated by integrating the absolute relative block-base velocity, as:

$$\rho_{II}(t)=\int\left|\dot{u}_{II}(t)-\dot{v}(t)\right|dt\cdot\tan\theta \tag{7}$$

Note that the coefficient tanθ is used again to account for the ratio between horizontal sliding and vertical settlements (Figure 2), similar to the conventional model described in Section 2.2.

2.4 Further assumptions

Application of both previously presented models in practice requires calibration of angle θ, used in Equations 3 and 7. According to Richards et al. (1993), θ can be obtained as the active Mononobe-Okabe wedge angle, namely angle ρ_A in Figure 1. In this context:

$$\theta\leq 45°+\frac{\varphi}{2} \tag{8}$$

where φ is the soil's friction angle. It is acknowledged that the failure mechanism considered by Richards et al. (1993) might not be as accurate as subsequent studies. Nevertheless, it is widely agreed that seismic bearing capacity failure is associated with a failure mechanism that remains shallower than the one for static failure under vertical loading. Therefore, this paper recommends the use of $\theta=45°+\varphi/2$, which is expected to provide conservative estimations of seismic settlements.

In addition, the proposed model incorporates the following assumptions:

- Seismic settlement accumulation occurs only due to (momentary) bearing capacity failure. Therefore, any effects of soil densification are not taken into account and should be considered separately (e.g. Massimino & Maugeri, 2013).
- The seismic bearing capacity (and thus the critical acceleration a_{cr}) is assumed to remain constant during the earthquake. The model is therefore not accounting for any soil hardening or softening effects.
- The superstructure is assumed to be infinitely rigid, hence any effects associated with its dynamic response are not considered.
- The model does not account for any rocking motion of the superstructure and it does not provide predictions of residual rotation/tilting.
- Finally, the effects of vertical input accelerations are considered negligible, while soil amplification effects can be only indirectly taken into account, through an uncoupled site response analysis and a subsequent adjustment of the input motion.

It is noted that the final three effects can be incorporated into an extended version of the proposed sliding-block model. This work is currently in progress at the University of Bristol.

3. APPLICATION FOR HARMONIC MOTIONS

3.1 Example applications

To demonstrate the response of the two models and illustrate their differences, a harmonic excitation is considered, consisting of 5 cycles with a maximum input acceleration of $\ddot{v}_o=1g$ and a period of T=1s.

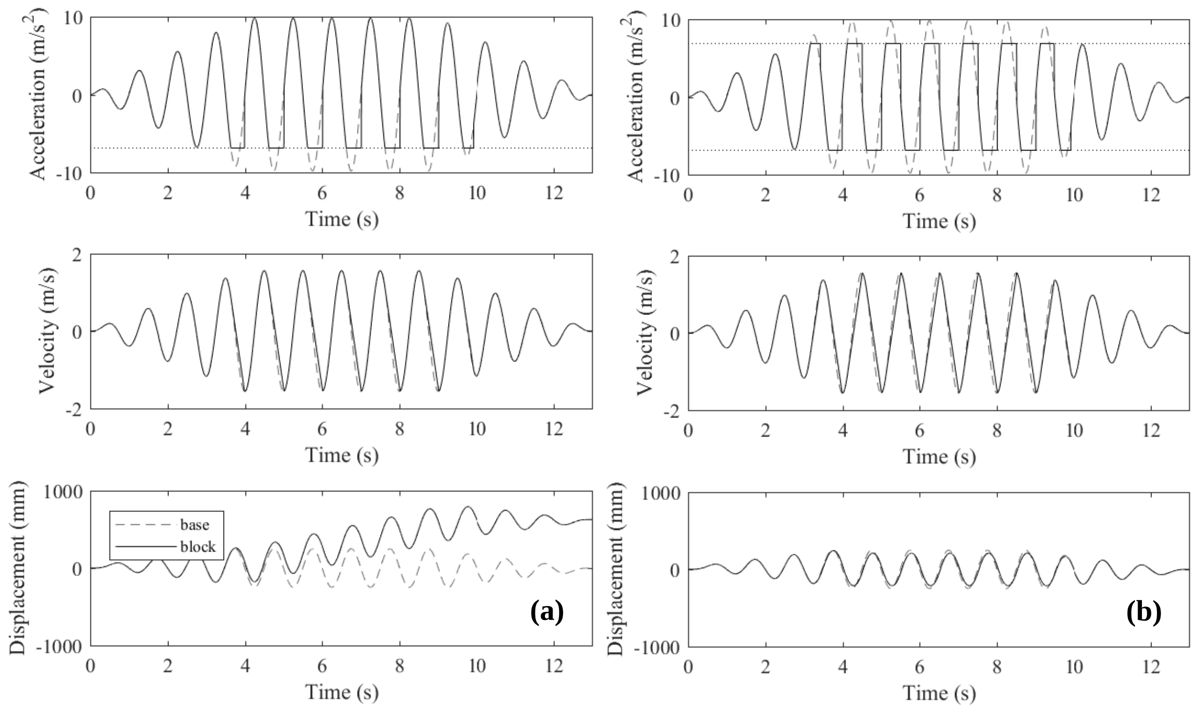

Figure 4. Horizontal accelerations, velocities and displacements of (a) the conventional and (b) the proposed sliding block model, under a harmonic motion, with a high critical acceleration ratio of $a_{cr}/\ddot{v}_o = 0.7$.

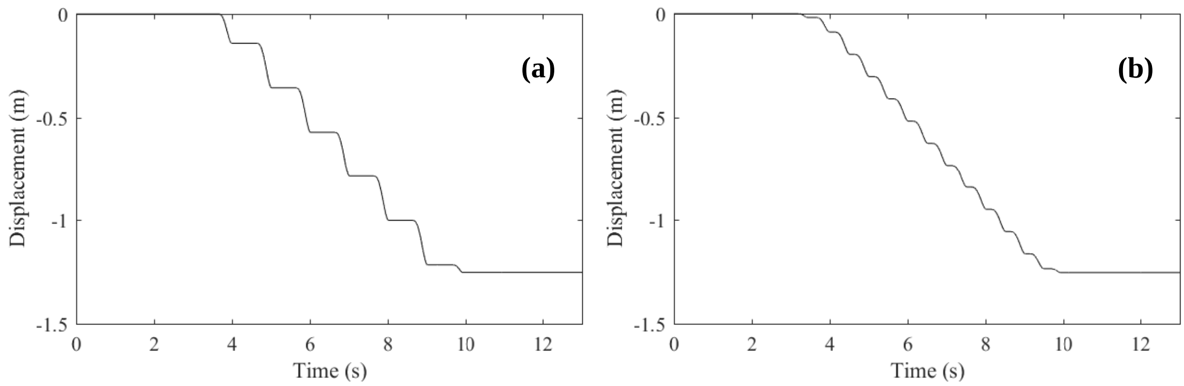

Figure 5. Accumulating settlements predicted by (a) the conventional and (b) the proposed sliding block model, under a harmonic motion, with a high critical acceleration ratio of $a_{cr}/\ddot{v}_o = 0.7$.

Note that the input motion also includes 4 ramp-up and 4 ramp-down cycles. Two cases are examined, namely a high critical acceleration ratio of $a_{cr}/\ddot{v}_o = 0.7$ and a low ratio of $a_{cr}/\ddot{v}_o = 0.1$. For the sake of simplicity, it is assumed that θ=45°, so that tanθ=1.

Focusing first on the case of $a_{cr}/\ddot{v}_o = 0.7$, Figure 4 presents the response of both models in terms of horizontal acceleration $\ddot{u}_I, \ddot{u}_{II}$, velocity $\dot{u}_I, \dot{u}_{II}$ and displacement u_I, u_{II} time-histories. These are plotted against the input motion $\ddot{v}, \dot{v}, v$. The corresponding settlements are shown in Figure 5.

As it may be observed from Figure 4a, Model I predicts an accumulating residual horizontal displacement of about 0.6m. Obviously, this horizontal movement is not representative of the footing's response, as it only accounts for one of two alternating inclined-plane sliding-block models of Figures 3a and 3b. The respective vertical settlement seems to accumulate in steps, once per each cycle of input motion, with the total settlement being equal to two times the horizontal drift, about 1.2m.

On the other hand, as shown in Figure 4b, the residual horizontal displacement of Model II remains close to zero. This is a more realistic representation of the footing's response under a symmetrical harmonic input excitation. Furthermore, as demonstrated in Figure 5b, Model II predicts a smoother

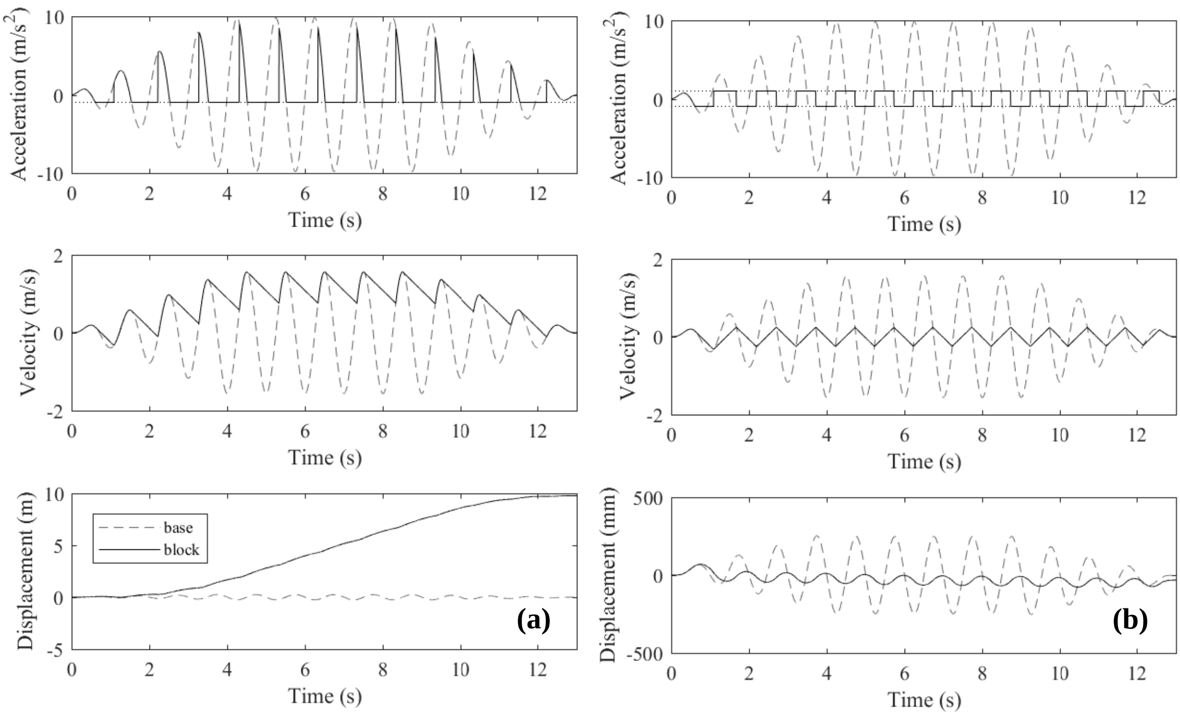

Figure 6. Horizontal accelerations, velocities and displacements of (a) the conventional and (b) the proposed sliding block model, under a harmonic motion, with a low critical acceleration ratio of $a_{cr}/\ddot{v}_o = 0.1$.

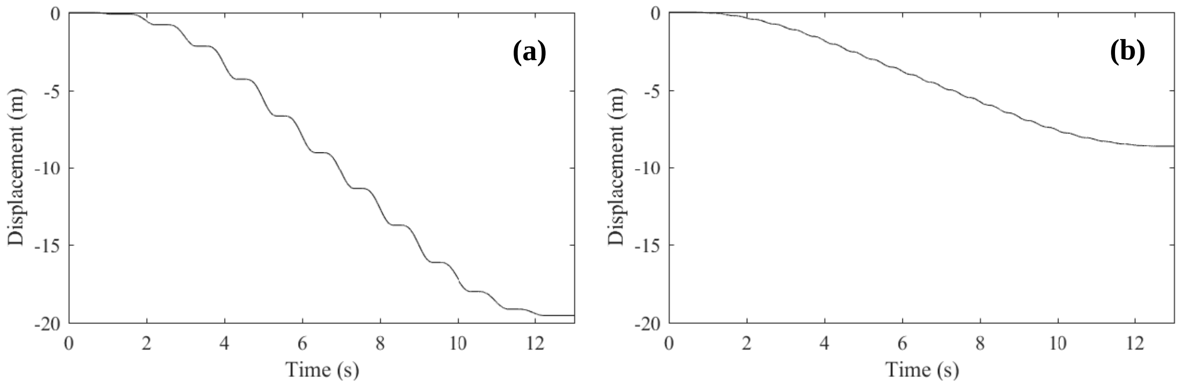

Figure 7. Accumulating settlements predicted by (a) the conventional and (b) the proposed sliding block model, under a harmonic motion, with a low critical acceleration ratio of $a_{cr}/\ddot{v}_o = 0.1$.

vertical displacement time-history, with settlement accumulating twice per cycle. Nevertheless, it is noted that despite the differences in the time-histories, the two models predict the same value of total settlement. This is attributed to the "stick-slip" nature of the response: sliding occurs only momentarily for each direction, hence the two alternating inclined-base models of Figures 3a and 3b are uncoupled. Therefore, considering only one of them and doubling the result yields the same prediction as the horizontal-base model of Figure 3c.

The same exercise is repeated in Figures 6 and 7, this time considering a significantly lower critical acceleration ratio of $a_{cr}/\ddot{v}_o = 0.1$. In this case, the difference between the two models becomes prominent. As shown in Figure 6b, the response in Model II has now transitioned to "slip-slip": constant sliding is occurring, with the block only instantly sticking with the base, twice per cycle, when the velocities $\dot{v}$ and $\dot{u}_{II}$ become equal. The horizontal velocity time-history follows a triangular pattern, with its mean value remaining close to zero. Horizontal displacements are limited, the residual horizontal drift is negligible and a smooth accumulation of vertical settlements is obtained, with a total (final) value of about 8m.

On the other hand, as demonstrated in Figure 6a, this behavior cannot be captured by Model I. The "slip-slip" nature of the response implies instant transitions from the model of Figure 3a to the one of Figure 3b, and vice versa. This behavior cannot be considered by examining only one of the two inclined-base models and simply "doubling" the resulting horizontal drift. This effect is clearly reflected in seismic settlement prediction. The horizontal velocity of the block in Model I remains close to the maximum horizontal velocity of the base, producing a significant horizontal drift of about 10m and a corresponding vertical settlement of about 20m. This is about 3 times larger than the settlement predicted by the proposed horizontal-base sliding-block model. Therefore, it becomes evident that for small critical acceleration ratios, the correction factor of 2·tanθ proposed by Richards et al. (1993) can be significantly over-conservative.

3.2 Parametric analysis

To better understand and quantify the limitations of conventional inclined-plane sliding-block analyses for the prediction of seismic settlement accumulation, a more detailed parametric investigation is conducted in this section. More specifically, the two models presented in Sections 2.2 and 2.3 are subjected to harmonic excitations, while the critical acceleration ratio $a_{cr}/\ddot{v}_o$ is varied from 0 to 1. The resulting settlement is normalized as:

$$\rho^* = \frac{\rho}{\ddot{v}_o T^2 N} \tag{9}$$

where $\ddot{v}_o$ is the base excitation amplitude, T is the excitation period and N is the number of cycles. When this normalization is applied, the results from the parametric analyses form two single lines, as shown in Figure 8a.

As it can be observed, the two models produce similar results for critical acceleration ratios larger than $a_{cr}/\ddot{v}_o > 0.5$. This is anticipated, as for high critical acceleration ratios, both models exhibit a "stick-slip" response, hence the two symmetrical alternating inclined-plane sliding-block models are indeed uncoupled and can be analyzed separately. Nevertheless, as the critical acceleration ratio decreases below 0.5 and Model II switches to a "slip-slip" response, Model I fails to predict accumulating settlements and provides increasingly over-conservative estimations.

This effect is clearly visualized in Figure 8b, which shows the variation with $a_{cr}/\ddot{v}_o$, of the ratio between the vertical displacements ρ_{II} obtained by the proposed model and the horizontal residual displacement u_I obtained through a conventional sliding block analysis. As expected, for critical

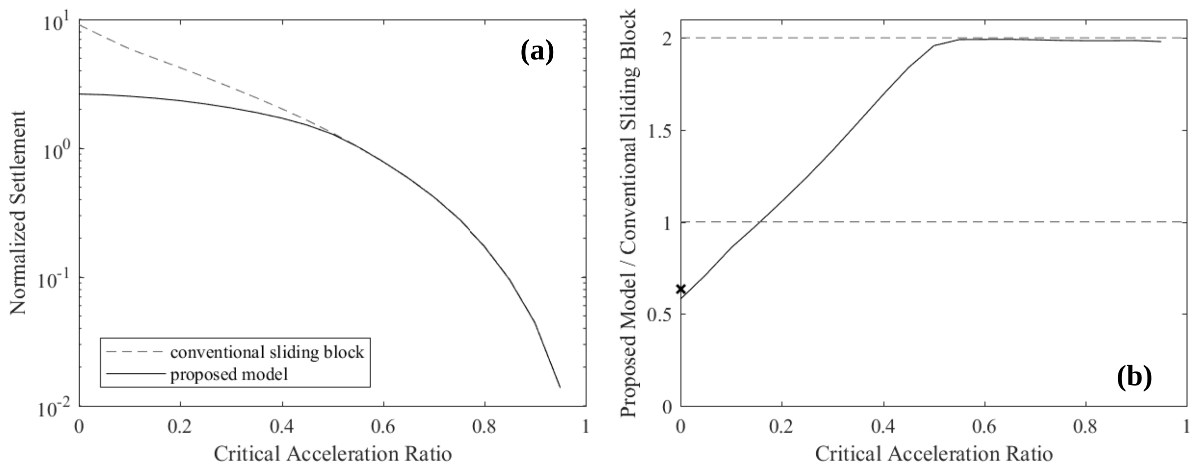

Figure 8. Variation, with the critical acceleration ratio of (a) normalized settlements ρ^* obtained by the proposed model and a conventional sliding block analysis (b) settlements ρ_{II} obtained by the proposed model normalized over the horizontal drift u_I predicted by conventional sliding block analyses.

acceleration ratios larger than $a_{cr}/\ddot{v}_o > 0.5$, it is $\rho_{II} \approx 2 \cdot u_I$. For smaller $a_{cr}/\ddot{v}_o$, a linear variation is obtained, tending to a value of about 0.6 at a_{cr}=0. The graph of Figure 8b, multiplied by tanθ, can be regarded as a correction factor to be employed in combination with a conventional inclined-plane sliding-block analysis, extending its applicability for the case of seismic settlements. For large critical acceleration ratios, this remains consistent with the factor of 2·tanθ proposed by Richards et al. (1993). However, its applicability now covers the whole range of critical acceleration ratios, from 0 to 1.

3.3 Analytical calculations and proposed correction factor

Among the cases presented in the above parametric investigation, the extreme scenario of a_{cr}=0 can be solved analytically. Subjected to a sinusoidal input excitation $\ddot{v}(t) = \ddot{v}_o \sin(2\pi t/T)$, the block on the inclined-plane model of Figure 3a (Model I, Equations 2-3) will accelerate downslope until it reaches a constant horizontal velocity of $\dot{u}_I = \ddot{v}_o T/2\pi$. In that case, the horizontal displacement accumulating during each cycle will be equal to:

$$u_{I,i} = \frac{1}{2\pi}\ddot{v}_o T^2 \tag{10}$$

The corresponding vertical settlement can be directly computed by multiplying the above with a factor of 2·tanθ.

On the other hand, in the horizontal-plane model of Figure 3c (Model II, Equation 6-7), the acceleration, velocity and displacement of the block would remain equal to $\ddot{u}_{II} = \dot{u}_{II} = u_{II} = 0$. Since the base velocity is harmonic and equal to $\dot{v}(t) = (\ddot{v}_o T/2\pi) \cdot \cos(2\pi t/T)$, the vertical displacement accumulating during each cycle will become equal to:

$$\rho_{II,i} = \int_0^T \left| \frac{\ddot{v}_o T}{2\pi} \cos\left(\frac{2\pi t}{T}\right) \right| dt \cdot \tan\theta = \frac{1}{\pi^2}\ddot{v}_o T^2 \tan\theta \tag{11}$$

The ratio between the vertical settlements of the horizontal-plane model and the residual horizontal displacements of the inclined-plane model can be computed from Equations 10 and 11 as:

$$\frac{\rho_{II,i}}{u_{I,i}} = \frac{2 \cdot \tan\theta}{\pi} \tag{12}$$

Firstly, it should be noted that the ratio calculated in Equation 12 does not depend on the characteristics of the input motion. Secondly, for θ=45°, the ratio becomes equal to 0.637. This value is shown with an X in Figure 8b and it is in very good agreement with the numerically obtained ratio for a_{cr}=0, with any minor differences being attributed to the ramp-up and ramp-down cycles used in the numerical analyses, which have not been considered in the analytical solution.

This analytical result can be implemented into a semi-analytical expression for the aforementioned correction factor, to estimate seismic settlements ρ of the horizontal-base sliding-block model (Model II) as a function of the horizontal drifting u from a conventional inclined-base sliding-block analysis (Model I):

$$\rho = \begin{cases} 2u\tan\theta & \text{for} \quad 0.5 \le \dfrac{a_{cr}}{\ddot{v}_o} \le 1.0 \\[2ex] \left[\dfrac{2}{\pi} + \left(4 - \dfrac{4}{\pi}\right)\dfrac{a_{cr}}{\ddot{v}_o}\right]\tan\theta & \text{for} \quad 0 \le \dfrac{a_{cr}}{\ddot{v}_o} \le 0.5 \end{cases} \tag{13}$$

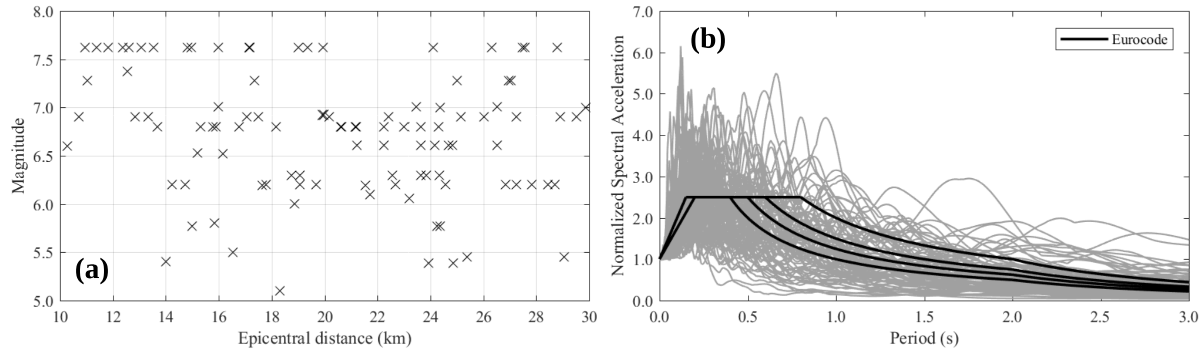

Figure 9. (a) Distribution of magnitudes and epicentral distances and (b) elastic response spectra, for the utilized database of excitation records.

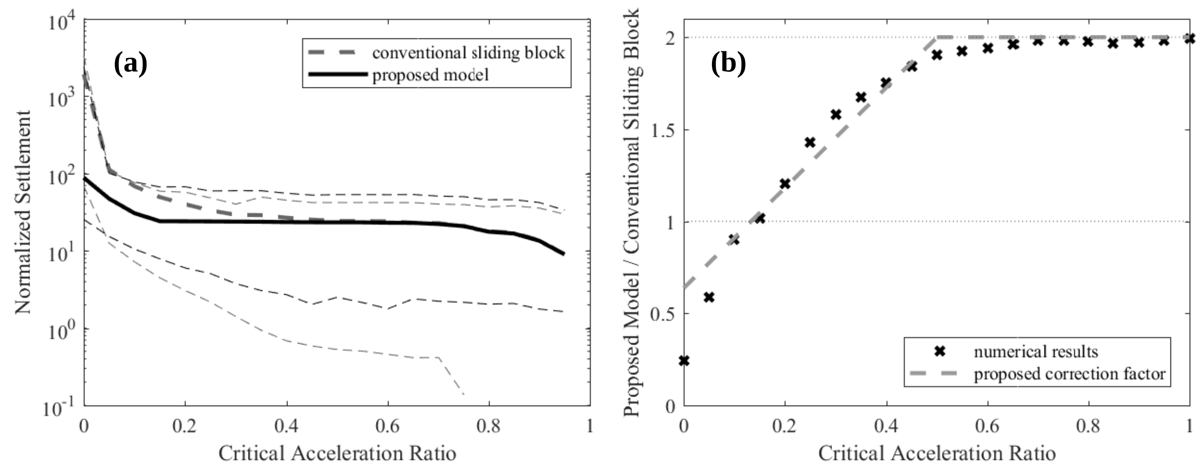

Figure 10. Variation, with the critical acceleration ratio of (a) normalized settlements ρ^* obtained by the proposed model and a conventional sliding block analysis (b) settlements ρ_{II} obtained by the proposed model normalized over the horizontal drift u_I predicted by conventional sliding block analyses.

4. PARAMETRIC APPLICATION FOR REAL EXCITATIONS

The semi-empirical factor proposed in the previous section was based on harmonic excitations. To verify its applicability for real seismic excitations, a parametric investigation was conducted, employing a total of 105 earthquake records from 28 different events, obtained from the web-based PEER Ground Motion Database (http://ngawest2.berkeley.edu/). Figure 9a shows the distribution of magnitudes and epicentral distances for the used records, while Figure 9b shows the corresponding normalized elastic response spectra (ξ=5%). As it can be observed, the utilized database covers a wide variety of earthquake excitations, indicating that the results of this study can be reliably generalized.

The results of the parametric analyses are presented in Figures 10a and b, in a format similar to the one in Figure 8. In this case, normalized settlements were obtained as:

$$\rho^* = \frac{\rho}{a_{\max} T^2 N_{eq}} \tag{14}$$

where a_{max} is the maximum acceleration, T is the predominant excitation period (obtained from the peak of the response spectra) and N_{eq} is the equivalent number of cycles.

Figure 10a shows a distribution which is directly comparable with the results of other researchers (e.g. Newmark, 1965, Richards & Elms, 1975, Whitman & Liao, 1985, Yegian et al, 1991), and can be used to derive another empirical correlation for earthquake-induced ground displacements. Nevertheless, emphasis is given to Figure 10b. Similar to harmonic motions, comparable values of seismic

settlements are predicted by the two models for large critical acceleration records $a_{cr}/a_{\max}$, where a "stick-slip" response is predominant. As the ratio decreases below 0.5, where the behavior switches to "slip-slip", the results obtained by the proposed model gradually decrease, as compared to the conventional sliding block model.
Furthermore, it can be observed that the semi-analytical factor of Equation 13, which is plotted on Figure 10b with a dashed line, is in notably good agreement with the obtained numerical results. It becomes evident that, with the aid of this correction factor, seismic settlements of shallow foundations can be directly estimated from a conventional inclined-base sliding-block analysis, similar to the ones used to estimate the residual seismic displacements of slopes and retaining walls. In this regard, the proposed factor can also be combined with any of the empirical, analytical, deterministic or probabilistic relations available in the literature, which allow to estimate residual ground displacements as a function of readily available design parameters, such as the peak acceleration a_{max}, the peak velocity v_{max} and/or the predominant excitation period T.

5. CONCLUSIONS

The presented paper extends the sliding block model originally proposed by Richards et al. (1993) for the estimation of seismic settlements developing in shallow footings, subjected to large earthquake excitations. According to the original approach, the settlement accumulation mechanism can be simulated with the simplified mechanical analogue of two alternating inclined-base sliding-block models. Based on this assumption, Richards et al. (1993) propose the performance of a conventional inclined-plane sliding-block analysis similar to the ones often used for slopes and retaining walls, and the subsequent multiplication of the result with a correction factor of $2 \cdot \tan\theta$, with θ being the angle of the inclined base.
However, it is demonstrated herein that the aforementioned simplification is only valid for large critical accelerations, close to the maximum input acceleration. For smaller critical acceleration ratios, the Richards et al. (1993) approach provides over-conservative results and can over-predict seismic settlements by a factor of 3. To remedy this limitation, a more accurate mechanical analogue is employed, namely a rigid block sliding on a horizontal base, with vertical settlements accumulating whenever sliding occurs. This model provides more reliable results for the whole range of critical acceleration ratios, as it can capture both "stick-slip" and "slip-slip" behaviors.
To aid the application of the proposed model in practical problems, a semi-analytical correction factor is proposed, which can be used in combination with any of the existing deterministic or probabilistic relations available in the literature for earthquake-induced permanent ground deformations, and extend their applicability to the case of shallow foundations. Although this factor is initially derived for harmonic excitations, its validity is also established against a large database of real excitation records.
Finally, it is acknowledged that the proposed model does not account for soil densification effects, soil hardening or softening, vertical accelerations and site amplification. Most importantly, in its present form, it does not provide predictions of residual rotation/tilting, while it does not consider the dynamic response of the superstructure. These effects are currently explored as part of ongoing research at the University of Bristol.

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