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ROLE OF SLIDING BLOCK ROTATION ON EARTHQUAKE-INDUCED PERMANENT DISPLACEMENT OF EARTH SLOPES

A. Lashgari[1], Y. Jafarian[2]

[1]Department of Civil Engineering, Semnan University
Semnan, Iran
a.lashgari@students.semnan.ac.ir

[2] Geotechnical Engineering Research Center, International Institute of Earthquake Engineering and Seismology
Tehran, Iran
yjafarianm@iiees.ac.ir

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Abstract. *Different methods are available for estimating earthquake-induced permanent deformation of earth slopes and embankments. Due to its simplicity, Newmarkian rigid block analogy has received considerable attention among the geotechnical practitioners and researchers. Since the conventional Newmarkian analogy has considered many limiting assumptions, conservative and unconservative estimate of sliding displacement would be possible. Thus, researchers have proposed many modifications to enhance the realistic features of this method. In reality, it is anticipated that the downward rotational (stabilizing) movement of the soil mass can significantly affect the yielding acceleration of the presumed slip surface. In this paper, the mentioned modification is numerically implemented to the conventional formulation of the Newmark approach for actual earthquake excitations. The results are presented for several conditions including the conventional rigid block, decoupled assumption of sliding and slope response, coupled consideration of sliding and slope response, and decoupled assumption with the effect of sliding block rotation. According to the results of this study, the period ratio (the ratio of natural period of slope to the mean period of input motion) and the length of slip surface can significantly vary the permanent displacement of sliding mass for these conditions.*

1 INTRODUCTION

Evaluation of earthquake-induced deformation of earth embankments and slopes is a matter of high importance for geotechnical engineers. Numerical and analytic methods could be used to calculate the permanent displacement of earth slopes . Since numerical methods with an appropriate constitutive model commonly need many soil parameters, engineers might be more interested to use analytic and semi-analytic methods. Among the analytic and semi-analytic methods, Newmark rigid block method [2], because of being simple, has the most applications. But in the initial form of this method, the effect of system response and rotation is not considered. Thereafter, the subsequent analyses considered the system response in the calculation of displacement through the coupled and decoupled procedures ([6]; [8]; [7]; [3]; [4]). Contrary to the decoupled assumption of system response and sliding, the dynamic response of the sliding mass and the permanent displacement are modeled together in the couple method so that the effect of plastic sliding displacement on the ground motions is taken into account [11]. Geometrically, downward movement of the sliding mass tries to stabilize the block; thereby increasing the yield acceleration. Such modification was initially proposed and formulated by Stamatopoulos [5] for the sliding block method and implemented within a decoupled analysis by Baziar et. al. [9].

The current study compares the permanent displacements which are obtained by the rigid-block, decoupled, coupled, and modified decoupled analyses. The latter analysis considers the effect of block rotation through the decoupled framework in the permanent displacement of earth slopes.

2 TYPES OF PERMANENT-DISPLACEMENT ANALYSIS

Several modifications of the initial Newmark's method were proposed to yield more accurate estimates of slope displacement by modeling the dynamic slope response more rigorously. Some of them together with the original sliding block method are summarized in the following sections.

2.1 Rigid-block analysis

The rigid-block model assumes that permanent deformation triggers once the earthquake-induced accelerations acting on a slide mass exceed the yield resistance on the slip surface. The sliding resistance is quantified by the seismic yield coefficient (k_y). Some limiting assumptions are including in this method for simplicity [11]:

1. The static and dynamic shearing resistances of the soil are taken to be the same ([2]; [12]).
2. The critical acceleration is not strain dependent and thus remains constant throughout the analysis ([2]; [13]; [12]; [14]).
3. The upslope resistance to sliding is taken to be infinitely large such that upslope displacement is prohibited ([2]; [12]; [14]).
4. The effects of dynamic pore pressure are neglected. This assumption generally is valid for compacted or overconsolidated clays and very dense or dry sands ([2]; [13]).
5. The effect rotation is not considered ([5]; [9]).

2.2 Decoupled analysis

This analysis, which was presented by Makdisi and Seed [13], is based on a rigid block but the dynamic response of the system is calculated to obtain the equivalent acceleration. The equivalent horizontal acceleration (HEA) is the time history of acceleration acting on the presumed sliding block. Therefore, instead the earthquake acceleration, the equivalent acceleration which contains the system response is applied to the block for displacement calculation. In this analysis rotation is not considered too rigid-block analysis.

2.3 Coupled analysis

The decoupled analysis does not consider the dynamic response of the slip, while this response is important. In a fully coupled analysis, the dynamic response of the sliding mass and the permanent displacement are modeled together so that the effect of plastic sliding displacement on the ground motions is taken into account [3]. In this analysis similar to two analysis previous rotation is not considered.

3 THE EFFECT OF BLOCK ROTATION

Stamatopoulos [5] considered dynamic motion of the Newmarkian sliding rigid block as a perfectly flexible chain sliding along planes with gradually gentler inclinations. This investigation has revealed that neglecting the downward-movement effect in the conventional sliding block analysis results in overconservative displacements. Downward-displacement effect would be significant in the case of smaller slippage lengths where downward-stabilizing-movement is predominant. For actual input ground motions, Stamatopoulos [5] concluded that downward-stabilizing effect would be insignificant when the ratio of yield acceleration to peak ground acceleration takes values greater than 0.2. As mentioned earlier, in spite of its advantage in considering the downward-motion effect, the model proposed by Stamatopoulos [5] does not take into account the effect of dynamic system response. It was found that the less is the length of sliding surface, the bigger gets the rotation effect and the created displacement gets smaller. Baziar et. al. [9] implemented the Stamatopoulos's model for decoupled analysis rather than the sliding block. They demonstrated how the rotation effect changes the permanent displacements obtained by the original decoupled solution.

4 THE ANALYSES

In this study, a computer code was written in time domain to capture the displacement time history using Rathje and Bray [3] equations for coupled and decoupled analysis. These equations were solved by using the time stepping method developed by Newmark [1] and also the central difference method. In the Newmark time step method, the coefficients β and γ can have different values. Figures 1 (a and b) shows the results obtained by coupled method for different values of β and γ. The earthquake motion of Pacoima Dam Downstream (PDD) station (horizontal component 175, T_m = 0.47 s) recorded from the 1994 Northridge earthquake, and Yerba Buena Island (YBI) motion (horizontal component 090, T_m =1) recorded from 1989 Loma Prieta earthquake were first scaled to MHA = 0.4g and used in the analyses. The curves were plotted in terms of the permanent displacements versus the period ratio; which stands for the ratio of system natural frequency and the mean period of input motion. This figure shows that the different values β and γ do not differ much if stability condition is provided. Stability condition for $\gamma = 0.5$ and $\beta = 1/6$ is $\Delta t \le 0.551 T_s$ and $\gamma = 0.5$ and $\beta = 0$ is $\Delta t \le \frac{T_s}{\pi}$ while for $\gamma = 0.5$ and $\beta = 0.25$ is always stable.

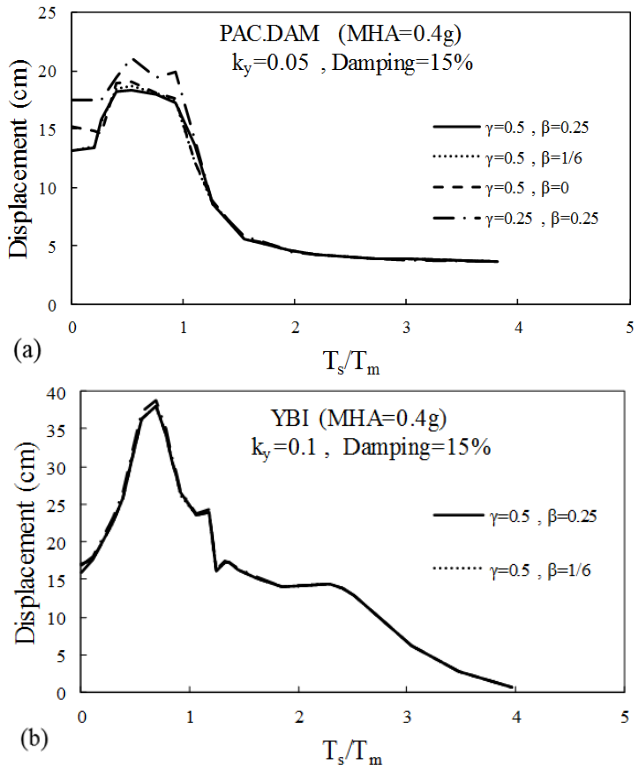

Figure 1. Results of coupled analysis using time stepping method with different values of β and γ for: (a); PAC.DAM k_y=0.05; (b) YBI, k_y=0.1.

As mentioned before, two numerical methods including the Newmark [1] time step and the central difference methods have been compared for coupled analysis, as shown in figure 2. The coupled analysis with these methods were carried out using the input motions of PAC.DAM with $k_y = 0.05$ and YBI with $k_y = 0.1$. The comparison shown in figures 2 (a and b) confirm that these methods yield similar results if stability condition is provided. Stability condition for finite difference method is $\Delta t \le \frac{T_s}{\pi}$.

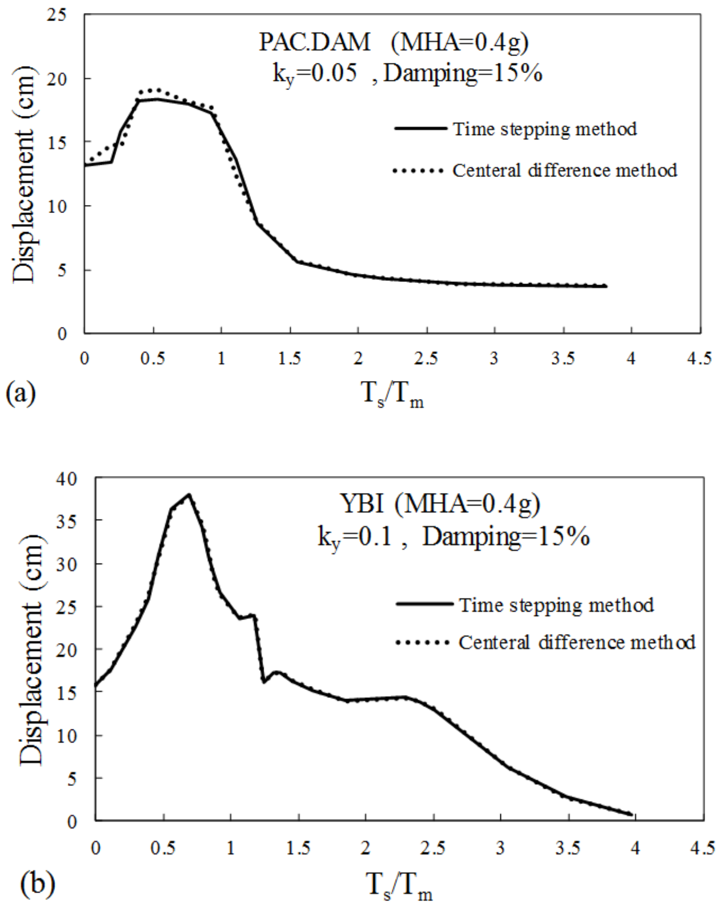

Figure 2. Comparison between the results of coupled analysis using time stepping and central difference methods for: (a); PAC.DAM k_y =0.05; (b) YBI, k_y =0.1.

Figure 3 compares the results of rigid block, decoupled, and coupled analyses for the yield acceleration of 0.05g subjected to YBI (see Figure 3a) and TAP (see Figure 3b) motion (horizontal component 051, T_m=0.99) recorded from 1999 Chi-Chi earthquake (scaled to MHA = 0.4g). This figure shows that the rigid block analysis is not conservative always. In low period ratios (T_s / T_m), the rigid block analysis, predicts unconservative displacement but it is conservative in large period ratios. As the figure illustrates, in low period ratios (T_s / T_m), the decoupled method compared with the coupled one, predicts the displacement more conservatively, but in larger period ratios, the coupled predicts larger displacements compared with the decoupled method. For systems with larger values of large fundamental periods, a decoupled analysis may predict smaller displacements than a fully coupled analysis [3]. Figure 3b, however, shows that the decoupled method obtains invariably conservative displacements for the whole range of period ratio.

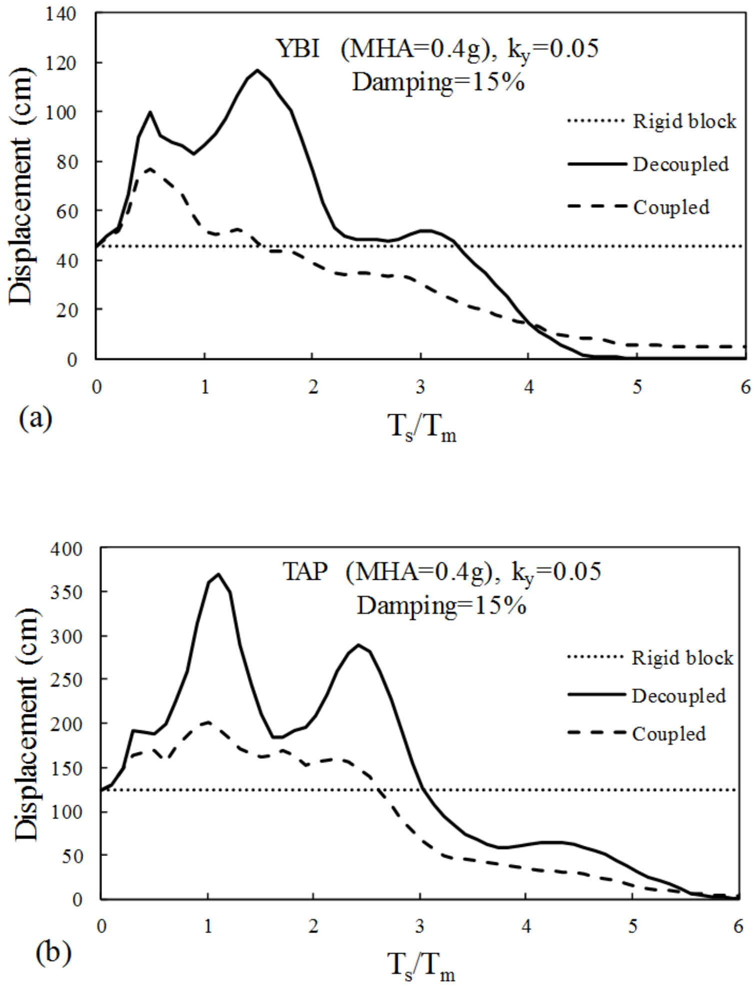

Figure 3. Permanent displacements obtained by coupled, decoupled, and rigid block analyses using time stepping and central difference method for: (a); PAC.DAM k_y =0.05; (b) YBI, k_y =0.1.

The coupled and decoupled permanent displacements shown in Figure 3 were calculated based on the formulations presented by Rathje and Bray [3] which ignore the effect of block rotation and the consequent increase in yielding acceleration. The formulations presented by Stamatopoulos [5] and Baziar et. al. [9] for the consideration of rotation in sliding block and decoupled analyses have been also coded in the current study using the time stepping method. There would be an opportunity to compare the permanent displacements obtained from the mentioned analyses and to evaluate the role of block rotation on the resultant displacements.

Figure 4 compares rigid block, modified rigid block, decoupled, modified decoupled, and coupled analyses using YBI and TAP records for two different sliding lengths and $k_y = 0.05g$. The results are presented in terms of permanent displacements versus the period ratio. As shown in the figure, modification for the rotation effect obtains smaller displacements in general. The decoupled approach obtains the most conservative displacement especially for the small period ratios and for the period ratios larger than 3 the original sliding block model obtains the greatest values. For the period ratios larger than 3, the decoupled and coupled displacements are relatively close together. It is impossible to make a clear conclusion for the difference between the modified decoupled and coupled displacements. However, modification of the decoupled method for rotation declines the calculated displacements to the level of coupled displacements. As this figure indicates, difference between the calculated displacements is also dependent to the characteristics of input motion. Furthermore, as previously indicated, it is evident from this figure that downward-stabilizing effect is major in smaller slippage lengths.

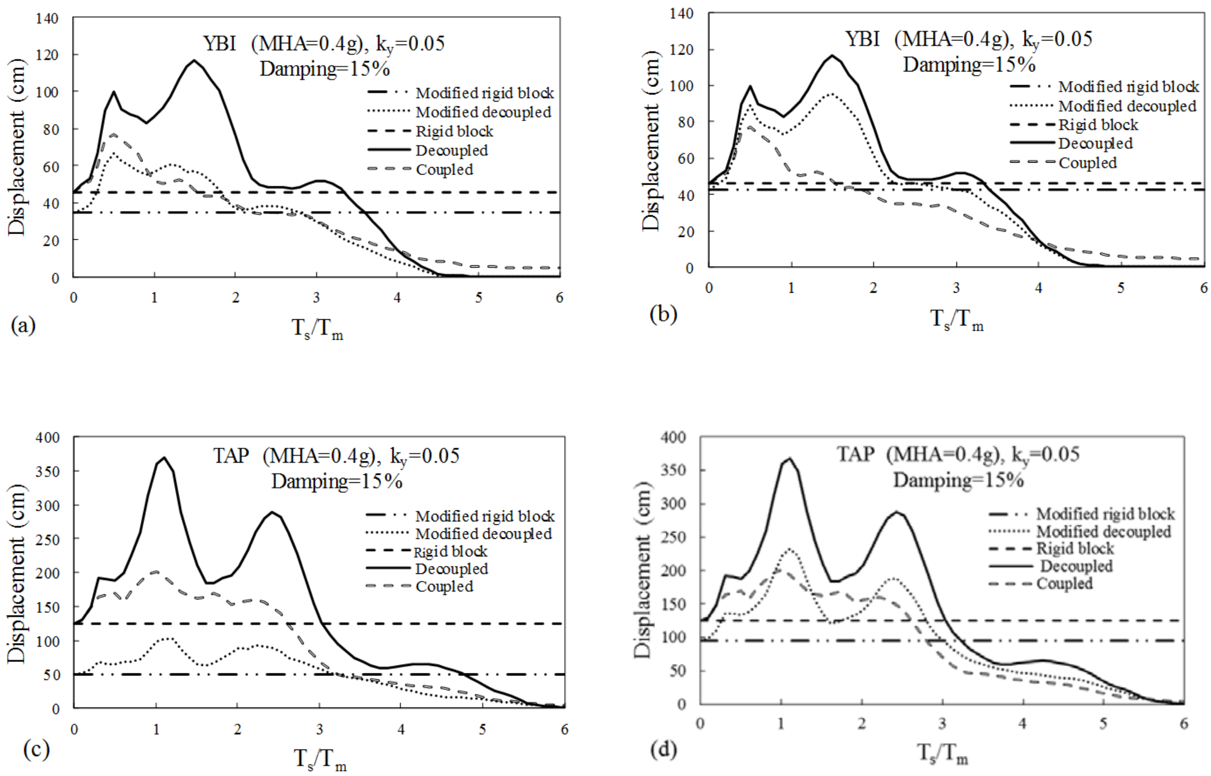

Figure 4. Comparison between the displacements of coupled, decoupled, sliding block, modified decoupled, and modified sliding block analyses versus period ratio for: (a) YBI, slippage length 10 m ; (b) YBI, slippage length 50 m; (c) TAP, slippage length 10 m; (d) TAP, slippage length 50 m.

The rotation of block, which is an inherent response of sliding block, plays an important role in the displacements obtained by rigid block and decoupled analyses. When sliding surface is shallower, lower contribution of sliding mass displacement is involved in calculating the whole dynamic response of slope body [6]. Based on the results shown in the present study, the mentioned modification for accumulated displacements is significant for smaller slippage lengths, i.e. shallow depths, for both rigid block and decoupled analysis.

5 CONCLUSION

Rigid block, decoupled, and coupled analyses were coded for estimating the earthquake-induced permanent displacement of earth slopes and embankments. To calculate the seismic response that utilized in the decoupled and coupled analysis the numerical time step methods and the central difference method were used. The numerical methods do not differ much if stability condition is provided.

Similar to the previous studies, it was shown that the rigid block and decoupled analysis do not obtain conservative displacement in any condition and it depends on the period ratio and the characteristic of input motion. . The modified rigid block and decoupled analyses which account for the role of sliding lock rotation have been implemented for calculation of permanent deformation of earth slopes. The values of permanent displacement were calculated using the coupled, decoupled, sliding block, modified sliding block, and modified decoupled analyses. Comparison demonstrates that the decoupled approach obtains the most conservative displacement especially for the small period ratios and for the period ratios larger than 3 the original sliding block model obtains the greatest values. For the period ratios larger than 3, the decoupled and coupled displacements are relatively close together. Consideration of the rotation effect significantly reduces the resultant permanent displacement obtained by the decoupled method. This effect is more profound for the small slippage length. In fact for the earthquake-induced landslides with considerable slippage length the role of block rotation is negligible in the decoupled and sliding block analyses.

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