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DEVELOPMENT OF A METHODOLOGY FOR ESTIMATING SIMPLIFIED SEISMIC SLOPE DEFORMATION OF LEVEES WITH SEEPAGE CONTROL MEASURES

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ABSTRACT

Seepage control measures of levee systems such as cutoff walls are susceptible to damage from lateral deformations of levees under seismic excitations. Seismic evaluation should assess the impacts of these deformations on the serviceability of seepage control measures.

Simplified procedures, based on Newmark (1965) sliding block analysis such as the Makdisi and Seed (1978) method are used widely to assess seismic slope deformations in dams and embankments. However, these methods are based on simplified assumptions, have significant limitations, and do not account for soil non-linearity. Alternately, rigorous analysis based on numerical modeling such as FLAC can be quite time consuming and expensive.

A methodology based on the Bray and Travasarou (2007) procedure is proposed for simplified seismic slope deformation evaluation of levees. This paper presents our studies on evaluating seismic slope deformations using the Bray and Travasarou (2007) procedures for four selected levee sections with proposed seepage control measures in California, USA. Comparisons are made between the proposed methodology and several other methods.

Based on the results, it is believed that the proposed methodology can be used to evaluate the impact on the serviceability of seepage control measures, of seismic slope deformations of levees which could be subjected to a strength loss due to the occurrence of soil liquefaction.

Keywords: Levee; Seismic Lateral Slope Deformation; Seepage Mitigation; Simplified Procedures

INTRODUCTION

Seepage control measures of levee systems such as cutoff walls are susceptible to damage from lateral deformations of levees. Seismic evaluation should assess the impacts of these deformations on the serviceability of seepage control measures.

Simplified procedures, based on Newmark (1965) sliding block analysis such as the Makdisi and Seed (1978) method are used widely to assess seismic slope deformations in dams and embankments. However, these methods are based on simplified assumptions, have significant limitations, and do not account for

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soil non-linearity. Alternately, rigorous analysis based on numerical modeling such as FLAC (Itasca, 2007) can be quite time consuming and expensive.

Recently, Bray and Travasarou (2007) proposed a simplified procedure to assess seismic deformations of earth/waste slopes. A methodology based on Bray and Travasarou (2007) procedure is proposed for simplified seismic slope deformation evaluation of levee sections. This paper presents our studies on evaluating seismic slope deformations for four selected levees with the proposed seepage control measures in Northern California, USA. Comparisons are made between the proposed methodology and several other methods including the method proposed in the Draft Guidance by the California Department of Water Resources (DWR, 2008).

SIMPLIFIED SEISMIC SLOPE DEFORMATION ANALYSIS

The deformation of a slope can be attributed to either volumetric compression or deviatoric shear deformation. The mechanism that results in deviatoric shear deformation is different from that resulting in volumetric compression. The deviatoric shear deformation is the subject of this paper. Simplified procedures typically refer to three different classes: (1) procedures with the rigid sliding block assumptions; (2) procedures with a decoupled stick-slip deformable sliding block model; and (3) procedures with a coupled stick-slip deformable sliding block model. Within the confine of this paper, it is not possible to present full discussions on these available simplified procedures, but, some of the most commonly used simplified procedures are briefly discussed in the sections that follow.

Rigid Sliding Block Analysis

The conventional Newmark rigid sliding block model assumed the sliding mass is not deformable and the deformation is completely attributed to the slippage of the sliding block. There are some other simplified procedures that follow the same assumption (Lin and Whitman, 1986; Ambraseys and Menu 1988; and Yegian et al, 1991). These procedures are known not to capture accurately the dynamic response of a deformable earth structure potential sliding mass during earthquake shaking.

Decoupled Simplified Seismic Slope Deformation Analysis

There are several simplified procedures that employed the conventional Newmark rigid sliding block model, but with improvements to account for the deformability of the sliding mass (e.g., Makdisi & Seed, 1978; Bray & Rathje, 1998). Nevertheless, the dynamic response of the sliding mass (i.e., dynamic deformation) and the rigid sliding block displacement are calculated in a decoupled manner. They have been shown to be overly conservative or lightly unconservative depending on the slope properties (Bray & Travasarou, 2007).

Coupled Simplified Seismic Slope Deformation Analysis

Bray & Travasarou (2007) proposed a new simplified semi-empirical predictive model for estimating seismic lateral slope displacements based on a fully non-linear coupled stick-slip deformable sliding model originally proposed by Rathje and Bray (2000). Compared to previous simplified procedures, the Bray and Travasarou procedure has the following advantages.

- A non-linear coupled stick-slip deformable sliding block model offers a more realistic representation of the dynamic response of an earth structure by accounting for the deformability of the sliding mass and by considering the simultaneous occurrence of its nonlinear dynamic response and periodic sliding episodes.

- An augmented database of hundreds of earthquake recordings provides the opportunity to better characterize the important influence of ground motions on the seismic performance of an earth structure.
- Realistic values of the initial fundamental period and yield acceleration coefficient for a wide range of earth structures were used.

The Bray and Travasarou procedure has proved to provide estimates of seismic displacement that are generally consistent with documented cases of earth dam and solid-waste landfill performance. . They also provided assessments that are not consistent with other simplified methods, but did so with an improved characterization of the uncertainty involved in the estimate of seismic displacement.

PROPOSED METHODOLOGY FOR SIMPLIFIED SESIMIC SLOPE DEFORMATION

A flowchart illustrating the proposed methodology for use with the Bray and Travasarou (2007) predictive model is presented in Figure 1. Brief explanations about primary steps are presented in the sections that follow.

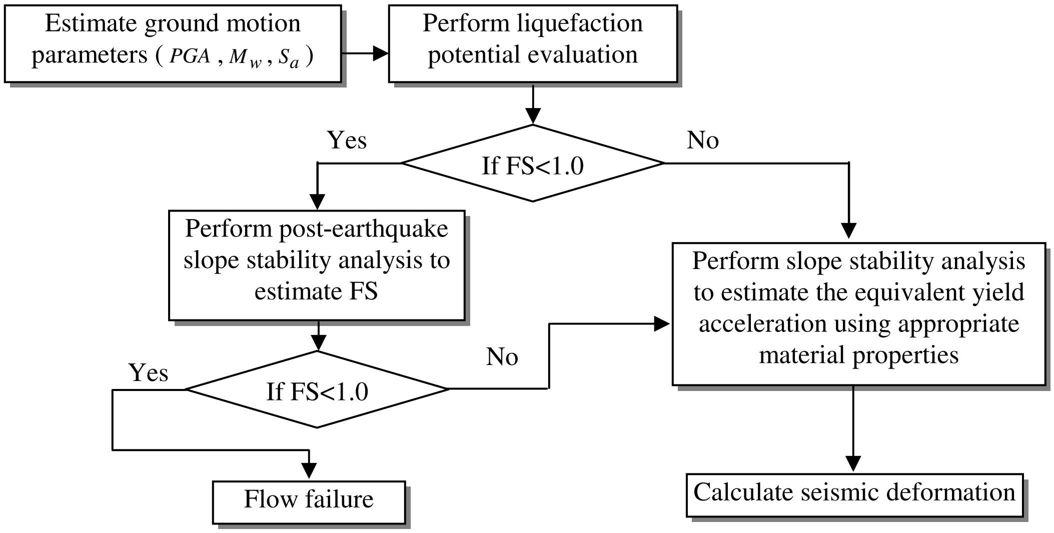


Figure 1. Flowchart showing the proposed methodology for estimating seismic slope deformation

Estimation of Ground Motion Parameters

Ground motion parameters required include the moment magnitude (M_w), the peak ground acceleration (PGA), and the spectral acceleration (S_a) of the input ground motion at a period of 1.5 times of the initial fundamental period (T_s) of the sliding mass ($S_a(1.5T_s)$).

Evaluation of Soil Liquefaction Potential

The occurrence of soil liquefaction is a key factor to the seismic slope deformation. It is known that, if soil liquefaction is not triggered, the deformation only occurs during the shaking and is often relatively small. However, if soil liquefaction is triggered, much larger deformation and possibly flow failure may occur. Numerous flow failures have occurred following liquefaction (Ishihara, 1984; Kokusho, 2003; Seed, 1987).

Liquefaction potential should be evaluated using recently developed procedures (i.e., Seed et al., 2003, and Idriss and Boulanger, 2004). Compared to the Youd et al. (2001) procedure, the two new procedures were developed based on augmented databases of field case histories and better understanding and treatment of site specific dynamic analyses, thus providing relatively more reliable and conservative results (Liao et al, 2010). The results of liquefaction potential evaluation will indicate what strength values should be used in estimating the yield acceleration.

Estimation of Equivalent Yield Acceleration

The yield acceleration has generally been adopted to represent the seismic resistance of an earth structure since it was first adopted by Newmark (1965) due to its important effect on seismic deformations. It is often assumed to be a constant during seismic shaking (i.e., earth materials do no undergo severe strength loss as a result of seismic shaking).

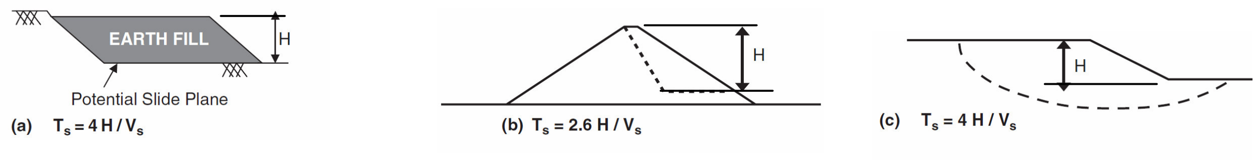
A recent study based on dynamic centrifuge model tests (Hata et al., 2009) showed that the yield acceleration can vary significantly during seismic shaking and it was their recommendation that the reasonable seismic residual displacement be determined by using the residual shear strength after shaking to consider the degradation of earth materials during shaking. Hereinafter, the term equivalent yield acceleration is defined as the yield acceleration that corresponds to the factor of safety equal to 1.0 and undrained residual shear strength is used for liquefied soils. The use of the equivalent yield acceleration can expand the application of simplified seismic deformation procedures to cases in which an earth material will undergo a relatively severe strength loss but with no flow failure occurring, which would otherwise have to be analyzed by means of advanced dynamic analysis such as FLAC modeling.

In our proposed methodology, the equivalent yield acceleration should be evaluated based on the residual shear strength estimated as follows.

- For sand-like materials, if the factor of safety (FS) against liquefaction is larger than 2.0, static shear strength values should be used. If the FS values are between 1.0 and 2.0, a reduction of 20% should be applied to the static shear strength. However, if liquefaction is triggered (FS < 1.0), residual shear strength of the liquefied soils should be used (Seed and Harder, 1990; Idriss and Boulanger, 2007).
- For clay-like materials, static shear strength values should be used if the over-consolidation ratio (OCR) is greater than 2.0. But the static shear strength should be reduced by 20% if the OCR value is smaller than 2.0.
- For all others, the same shear strength values should be used as in static analyses.

Calculating Initial Fundamental Period

It is known that the dynamic response characteristics of the potential sliding mass are also important to the seismic deformations. With all other factors held constant, the seismic deformations increase when the sliding mass is near resonance (Kramer and Smith, 1997; Rathje and Bray, 2000; Wartman et al, 2003). Per Bray and Travasarou (2007), the initial fundamental period (T_s) can be estimated as illustrated in Figure 2 based on the height (H) and the shear wave velocity (V_s) of the sliding mass.



(a) $T_s = 4H/V_s$ (b) $T_s = 2.6H/V_s$ (c) $T_s = 4H/V_s$

Figure 2. Estimating the initial fundamental period of the potential sliding mass (Bray and Travasarou, 2007)

Calculating Seismic Slope Deformation

The Bray and Travasarou predictive model is utilized to estimate the seismic slope displacement:

$$
\begin{aligned}
\ln(D) = & -1.10 - 2.83\ln(k_y) - 0.333(\ln(k_y))^2 + 0.556\ln(k_y)\ln(S_a(1.5(T_s)) + 3.04\ln(S_a(1.5(T_s)) \\
& - 0.244(\ln(S_a(1.5T_s)))^2 + 1.5T_s + 0.278(M-7) \pm \varepsilon \qquad (1)
\end{aligned}
$$

Where, D = seismic displacement in cm; k_y = equivalent yield acceleration in g;

T_s = initial fundamental period of the sliding mass in second; $S_a(1.5T_s)$ = spectral acceleration of the input ground motion at a period of $1.5T_s$ in g; ε = a normally distributed random variable with zero mean and standard deviation $\sigma = 0.66$.

It should be noted that Equation (1) is applicable for T_s values of 0.05 – 2 seconds. If T_s values are smaller than 0.05, the first term of Equation (1) should be replaced with -0.22.

SEISMIC DEFORMATION EVALUATION OF LEVEES WITH CUTOFF WALL SEEPAGE MITIGATION

Introduction to Four Selected Levee Sections

Four levee sections were selected from the area in which an entire levee system needs to be certified to meet the seepage criteria associated with the 200-year flooding event. The majority of the levee system needs to be either raised for meeting free board criteria using adjacent levees constructed next to the inboard slope or mitigated to pass seepage criteria using either cutoff walls or seepage berms as control measures, depending on the specific subsurface condition at different locations.

Cutoff walls constructed of soil-bentonite materials are recommended for underseepage or through-seepage mitigation at various locations. These cutoff walls are typically 3-4 feet wide and vary in depth depending on the subsurface conditions. They are susceptible to damage from lateral deformations of levees under seismic events. Seismic evaluation should assess the impacts of these deformations on the serviceability of cutoff walls as a seepage barrier.

Four representative sections mitigated with cutoff walls were selected for evaluating the seismic lateral deformations using the proposed simplified methodology: (1) Levee A with an 80-foot deep cutoff wall; (2) Levee B with a 50-foot deep cutoff wall; (3) Levee C with a 95-foot deep cutoff wall; (4)

Levee D with a 25-foot deep cutoff wall. These sections are graphically presented in Figure 3 with the modeled strata as well as the configuration of cutoff walls.

Ground Motion Parameters

Ground motion parameters were estimated using the computer program EZ-FRISK (Risk Engineering, 2005) for a design seismic event with a 200-year return period that is consistent with the design flood event. It is noted that the Next Generation Attenuations (NGAs) were used for their robustness. The estimated seismic ground motion parameters are listed in Table 1.

Liquefaction Potential Evaluation

The liquefaction potential evaluation was performed using the newly developed Seed et al procedure (Seed et al., 2003). In this study, the lower one-third of undrained residual shear strength was used for for liquefied soils to perform post-earthquake slope stability analyses. The results of liquefaction potential analyses along with the estimated undrained residual shear strength for liquefied soils are presented in Table 1. For granular soils with a FS value against liquefaction between 1.0 and 2.0, their shear strength was reduced by 20% and presented in Figure 3 (e.g., loosened silty sand in Figure 3c).

Table 1 Results of Ground Motion Parameters and Liquefaction Potential Evaluation

Levee Section	$V_{s,30}$ (ft/s)	M_w	PGA (g)	Depths of liquefied soils (ft)[1]	USCS classification of liquefied soils	$(N_1)_{60\text{-}cs}$[2]	$S_{u,r}$[3] (psf)
Levee A	760	6.6	0.16	N/A	N/A	N/A	N/A
Levee B	650	6.6	0.18	36 – 48	ML/SP	7.5	120
Levee C	700	6.6	0.18	25 – 43	SM	7.0	100
Levee D	650	6.6	0.18	24 – 27	CL-ML	7.5	120

[1] Depths measured from the levee crest; [2] Equivalent clean sand SPT blowcount;
[3] Undrained Residual Shear strength.

As it can be seen in Table 1, three out of four levee sections will be subjected to varying amount of strength losses due to the soil liquefaction under the design seismic event. It is noted that the magnitude of strength loss due to the liquefaction will be used as an indication of the conservatism of our proposed methodology for evaluating the simplified seismic slope deformation later in this paper.

Equivalent Yield Acceleration

In this study, computer program SLOPE/W (Geo-Slope, 2008) was used to calculate the equivalent yield acceleration for each section. Undrained residual shear strength was used for liquefied soils. Material properties of non-liquefiable granular soils were estimated using typical blowcount-based correlations. Undrained shear strength for cohesive soils obtained from triaxial consolidated undrained compression tests was used. The graphical outputs from SLOPE/W are presented in Figure 3. The areas bounded by black bold lines in Figure 3 represent the most critical potential sliding mass to the integrity of the cutoff wall found in the analyses. The estimated equivalent yield accelerations are shown in Table 2.

Initial Fundamental Period

Following the procedure recommended by Bray and Travasarou (2007), the estimated initial fundamental period for each section is presented in Table 2.

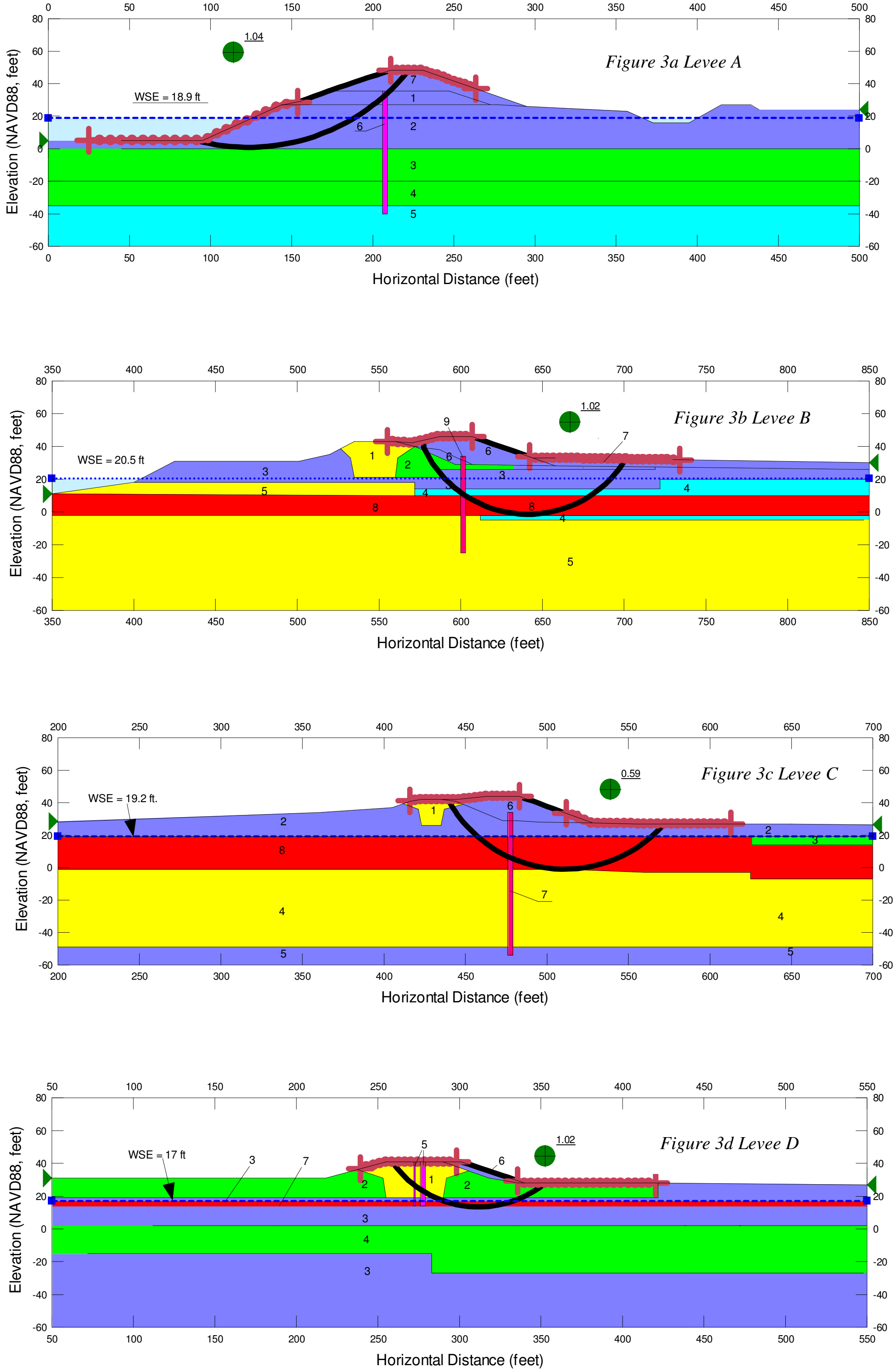


Figure 3 Results of SLOPE/W analyses of four selected levee sections

Seismic Slope Deformation

The response spectrum needs to be derived by running computer program EZ-FRISK to obtain $S_a(1.5T_s)$ values. Finally, the calculated seismic slope deformation at each section is presented in Table 2. As seen from Figure 3a, the most critical slip surface passes through the top 4 feet of the cutoff wall within the native blanket layer. The damage of the cutoff wall from about 30 cm lateral deformation is likely to be limited to the top portion. The integrity of the cutoff wall serving a water barrier between materials #2 and #5 is likely to be remained the same.

Table 2 Results of Calculated Seismic Lateral Deformations

Levee Section	k_y (g)	H (ft)	T_s (sec.)	$S_a(1.5T_s)$ (g)	Calculated. median displacement (cm)
Levee A	0.035	42	0.144	0.38	30
Levee B	0.045	51	0.314	0.38	39
Levee C	-	-	-	-	Flow liquefaction
Levee D	0.102	30	0.185	0.43	9

For Levee B, a deep seated slip surface passes approximately through the middle portion of the cutoff wall. The integrity of the cutoff is likely to be impeded due to an estimated lateral movement of 39 cm.

For Levee C, the liquefied material #8 formed a significant weak layer with the estimated residual shear strength of 100 pounds per square foot, which led to the occurrence of flow liquefaction. The integrity of the cutoff wall as a barrier would be completely compromised.

For Levee D, a short cutoff wall along with an adjacent levee was proposed to mitigate the potential through seepage deficiency. As seen in Figure 3d, the most critical slip surface passes through the lower half of the cutoff wall. Nevertheless, the integrity of the cutoff wall is not likely to be severely damaged since the estimated lateral deformation is only about 9 cm.

COMPARISON WITH OTHER SIMPLIFIED PROCEDURES

Since the development of the Newmark method in 1965, there have been several other simplified methods available for estimating the seismic deformations of slopes. For a comparative study, other representative methods along with the recommended DWR methods (DWR, 2008) were compared to the proposed methodology in this paper, namely, Makdisi and Seed (1978) method, Bray and Rathje (1998) method, the DWR method (2008).

For the Makdisi and Seed method, iterations are used to estimate the 1st natural period of potential sliding mass and maximum crest acceleration. The Seed and Idriss (1970) shear modulus reduction and damping curves were used for sandy material. The Vucetic and Dobry (1991) shear modulus reduction and damping curves were used for cohesive soils. Computer program EZ-FRISK was used to obtain spectral acceleration curves at various damping ratios.

For the Bray and Rathje method, the required maximum horizontal acceleration for a rock site with a shear wave velocity of 2500 ft/s, modal magnitude, and model distance were estimated by running computer program EZ-FRISK. Then the median displacement can be estimated from Equation (2):

$$\log_{10}\left(\frac{u}{k_{\max}\cdot D_{5-95}}\right)=1.87-3.477\cdot\frac{k_y}{k_{\max}} \qquad (2)$$

Where, $u =$ Newmark type displacement; $k_y =$ the yield acceleration; $k_{\max} =$ averaged horizontal acceleration; $D_{5-95} =$ during of input ground motion as the time between 5% and 95% normalized Arias Intensity.

For the DWR method, the $k_{\max}$ values and Newmark displacements were estimated using the curves shown in Figure 4. These curves were developed based on the results of site-specific dynamic analyses using 2-D equivalent linear finite element computer program QUA4M (Athanasopoulos, 2008).

For the three simplified methods, the same equivalent yield accelerations as those listed in Table 2 are used. The comparison of the simplified methods' estimates for seismic lateral deformations is presented in Table 3.

Table 3. Comparison of the Estimated Seismic Lateral Deformations

Levee Section	Proposed method (2009) (cm)	Bray & Rathje (1998) (cm)	Makdisi & Seed (1978) (cm)	DWR method (cm)	Quake/W Analysis
Levee A	30	20	10	28	6
Levee B	39	24	21	27	35
Levee C	Flow liquefaction	N/A	N/A	Unstable	N/A
Levee D	9	0.8	1.3	0.7	3

Note: Bray and Rathje (1998) and Makdisi and Seed (1978) procedures are not applicable to sections with significant strength loss of potential sliding mass due to soil liquefaction.

In addition to simplified methods, equivalent linear dynamic analyses were also performed to compute the simplified Newmark-type lateral displacement using computer program QUAKE/W (Geo-Slope, 2009). A total of ten input ground motions were used to compute the seismic lateral displacement. The identical shear modulus curves and damping ratio curves as used with the Makdisi and Seed method were utilized. The computed seismic lateral displacements are presented in Table 3.

As seen in Table 3, the proposed methodology based on the Bray and Travasarou procedure predicted the largest displacements for all levee sections. Makdisi and Seed method predicted the smallest displacements for Levees A and B. The displacements predicted by the DWR method are the closest to what the proposed methodology predicted for Levees A and B. Compared to the displacements computed from QUAKE/W program, all methods estimated greater displacements for Levee A. For Levee B with liquefiable soils, all other three methods estimated lower displacements than our proposed methodology. Our proposed methodology predicted greater lateral displacement for three Levees A, B, and D, The difference in the lateral displacement estimated with QUAKE/W and with our proposed methodology decreases with an increase in more significant strength losses from liquefiable soils.

It is of interest to note that all the existing simplified methods are proposed for estimating the seismic displacement of slopes/earthen structures without significant strength loss due to the liquefaction. However, there has not been any definition about the term "significance". In this paper, the authors proposed a ratio defined as the ratio of the yield acceleration for a levee before liquefaction to the equivalent yield acceleration for the same levee after liquefaction to define the significance of the strength loss. One more slope stability analysis is conducted each for Levees B, C, and D as if there is no liquefaction. The results of the estimated yield accelerations are also presented in Table 4.

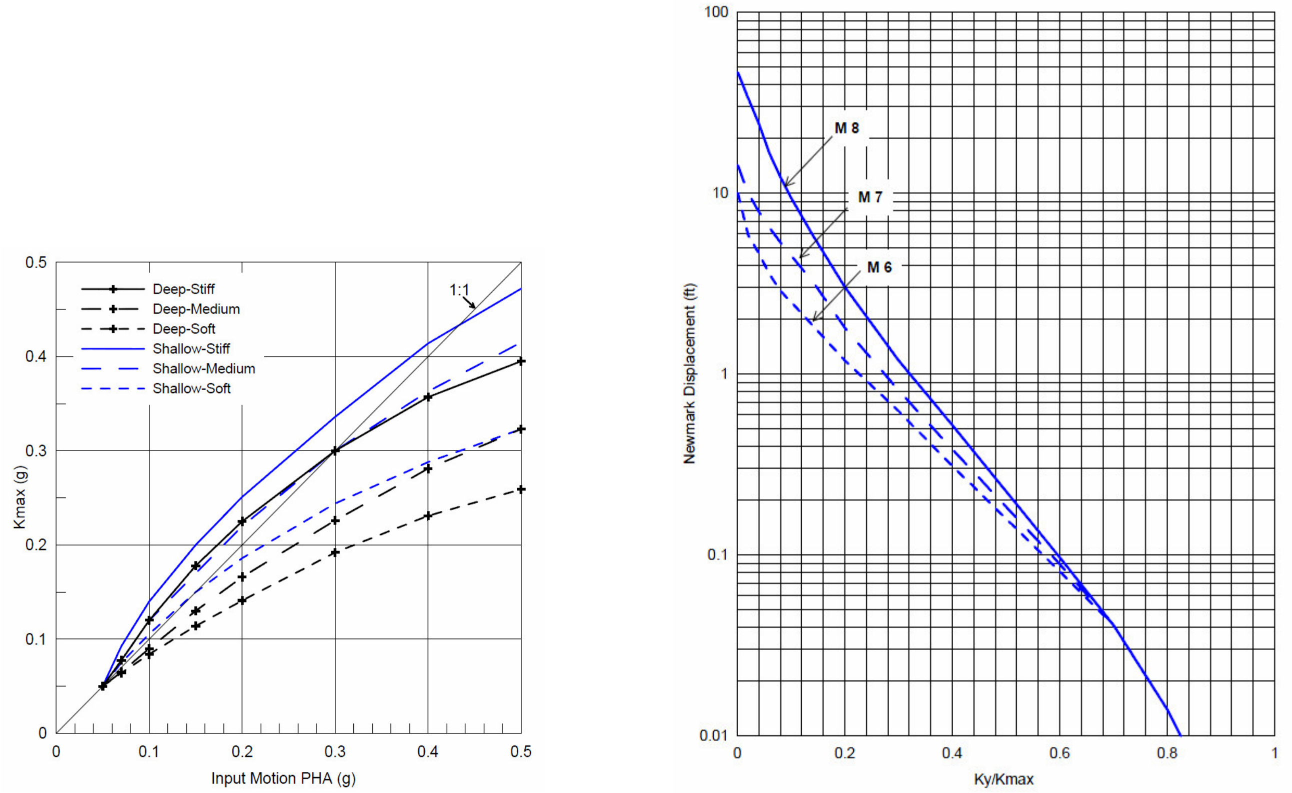


Figure 4. Recommended $K_{\max}$ vs input motion PHA (DWR, 2008) (left); Recommended Newmark displacement vs $k_y / k_{\max}$ (DWR, 2008) (right)

Table 4. Estimated Yield Acceleration for Analyses with and without Liquefaction

Levee Section	k_y (g)		Ratio of k_y
	Analyzed without Liquefaction	Analyzed with Liquefaction	
Levee A	0.035	0.035	1.0
Levee B	0.22	0.045	4.9
Levee C	0.25	N/A	N/A
Levee D	0.26	0.102	2.5

As seen in Table 4, the greater the strength loss due to the soil liquefaction, the larger the ratio of k_y. If the flow liquefaction occurs, the ratio is not applicable. Instead, the ratio equals 1.0 if there is no liquefaction-induced strength loss. The ratio of k_y maybe a good indication of significance of the strength loss due to soil liquefaction for estimating simplified seismic displacements. However, conclusions are made based on only four levee sections. To this end, further study is probably needed to better define the "significance" of the strength loss in terms of the ratio of k_y.

CONCLUSIONS

The proposed simplified analytical framework for estimating seismic slope deformations was developed not only for cases where a strength loss is not anticipated, but also for cases in which a strength loss is anticipated using the concept of the equivalent yield acceleration. This framework provides a means for practitioners to make reasonable estimates of seismic lateral deformation of levee sections without running a rigorous analysis which is usually too time-consuming and expensive.

The results of evaluating seismic slope deformation of four selected levee sections indicated that a cutoff wall as a seepage barrier could be damaged due to a lateral movement of potential sliding mass in a levee during seismic shaking. If liquefied foundation soils formed a weak layer under a levee that lead to a deep seated slip surface. This situation could result in a severe damage to the integrity of the cutoff wall as a seepage barrier.

Our comparative study indicated that the proposed methodology based on the Bray and Travasarou procedure will predict larger displacements than other currently existing simplified methods, and Makdisi and Seed method will generally predict the smallest displacements. It should be noted that these estimates obtained from simplified methods should be considered merely an index of anticipated seismic performance of the levee.

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