Seismic slope stability of earthen levees

La stabilité sismique de pente de digues en terre

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ABSTRACT: This study focuses on systematically studying the seismically induced deviatoric-type displacements for earthen levees. The study was based on levee sites representative of select California Central Valley regions. A wide range of input ground motions were used in an effort to capture and assess the variability in response and performance due to multiple possible earthquake scenarios. Dynamic, 2D, equivalent linear, finite element numerical analyses were performed using QUAD4M, to obtain accelerations and shear stresses for the three levee profiles. Four critical sliding surfaces were selected for the evaluation of permanent seismic deviatoric type displacements for each levee cross section: a shallow and a deeper sliding surface on both the landside and waterside. Seismic displacements were calculated using a decoupled equivalent-linear, Newmark-type approach. The observed variability in the computed seismic displacements due to the different input ground motions was significant and was greater than the variability observed due to differences in site conditions. Results from this study are compared to the Makdisi and Seed (1975) displacements vs k_y/k_{max} ratio, and recommendations are made on evaluating seismically-induced deviatoric displacements for levees.

RÉSUMÉ : Cette étude se fixe sur étudiant systématiquement les déplacements de deviatoric-type sismiquement induits pour les digues en terre. L'étude était fondée sur le représentant de sites de digue de Californie privilégiée régions de Vallée Centrales. Une grande variété de données fonde des mouvements ont été utilisés dans un effort pour capturer et évaluer la variabilité dans la réponse et l'exécution en raison des scénarios de tremblement de terre possibles multiples. Dynamique, 2D, l'équivalent élément linéaire et fini numérique analyse a été exécuté utilisant QUAD4M, pour obtenir des accélérations et des tensions de cisailles pour les trois profils de digue. Quatre surfaces coulissantes critiques ont été choisies pour l'évaluation de déplacements de type de deviatoric sismiques permanents pour chaque coupe transversale de digue : un peu profond et une surface coulissante plus profonde sur le landside et le bord de l'eau. Les déplacements sismiques ont été calculés utiliser une détaché équivalent-linéaire, l'approche de Newmark-Type. La variabilité observée dans les déplacements sismiques calculés en raison des mouvements de sol d'entrée différents était significative et était plus grand que la variabilité a observé en raison des différences dans les conditions de site. Les résultats de cette étude sont comparés au Makdisi et Seed (1975) les déplacements contre la proportion de k_y/k_{max}, et les recommandations sont faites sur évaluer les déplacements de deviatoric sismiquement-induits pour les digues.

KEYWORDS: levees, seismic slope stability, dynamic analysis, ground motions.

1 INTRODUCTION

Flooding is one of the most dangerous and costly natural hazards. Flood-protection systems are therefore important engineering systems for handling water resources, but also protecting urban areas, important civil infrastructure elements and agricultural land properties that lie in or cross potential floodplains. An important part of these systems are earthen levees, often originally created by the river's own overbank deposits, and then further improved by humans in an effort to use the rich land of the river floodplains and to provide flood protection for growing populations. The vast majority of river cities, now growing at increasing rates, are also protected from flooding by earthen levees, that can be viewed as series systems, where failure at one location or failure of one component can result in catastrophic failure of the entire protection system leading to tragic loss of life, substantial damage to buildings, homes and civil infrastructure, and significant impact on the economy of the surrounding areas.

Levees are very challenging engineering structures to study, in part because they are not typically well-engineered structures. Robust estimates as to the seismic vulnerability of earthen levees are needed as the government is moving towards reassessing the condition of our nation's flood protection systems. Unfortunately, there is little to no guidance as to how to evaluate the seismic vulnerability of levees with respect to seismically-induced permanent displacements. Since in seismic slope stability analyses the input acceleration time-history is the most important parameter (Bray, 2007) a systematic study of the dynamic response of earthen levees of varying soil stratigraphy and for a wide range of ground motions is needed.

As part of this study, three typical levee cross-sections were analyzed that are representative of the Stockton area, the West Sacramento area, and the Marysville area, in California. These are denoted by Levee types A, B, and C respectively, and are among the sites under study as part of the Urban Levee Project of the California Department of Water Resources.

2 DYNAMIC ANALYSIS

The geometry and soil stratigraphy of the three characteristic levee cross-sections and the criteria used for the selection of the input ground motion recordings and a list of these seismic motions are presented in detail by Athanasopoulos-Zekkos (2008 and 2010) and Athanasopoulos-Zekkos and Saadi (2012) and due to space limitations will only be summarized in this paper. Figure 1 shows the three levee cross-sections together with the Vs profile that was used in the analyses. A 2D, finite element, equivalent linear program called QUAD4M (Hudson et al., 1994 and Idriss et al., 1973) was used for performing the dynamic analyses. A wide range of ground motions (~1,500) was used in the present study to develop statistically stable estimates of dynamic response of levees for the three different levee sites and to also provide insight towards the effect of ground motion selection to the dynamic response of earthen levees. The ground motions were selected from the Pacific Earthquake Engineering Research (PEER, 2007) Center, NGA strong motion database. Four groups of input ground motions were used in the analyses, each group scaled to a specified PGA_{input}: 0.1g, 0.2, 0.3g, and 0.4g respectively.

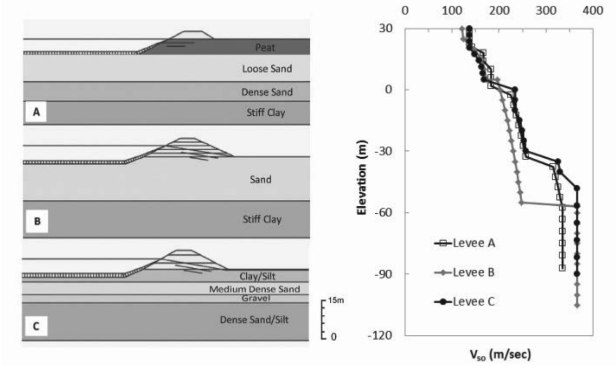

Figure 1.Levee geometry and soil stratigraphy and corresponding shear wave velocity profile for levee sites A, B and C. Elevation 0m is at the ground surface on the landside (from Athanasopoulos-Zekkos, 2010).

Four sliding surfaces were pre-selected based on previous slope stability analyses (URS 2008) for identifying the most critical sliding surfaces, and the seismically induced deviatoric displacements were computed using a Newmark-type approach. In the original Newmark method, the sliding mass is considered to be a rigid block, however in this study its dynamic response was also considered. As suggested by Seed and Martin (1966), the effects of the dynamic response of the sliding mass itself can be significant in the overall displacements. Therefore, the concept of the equivalent acceleration time history is used to account for this effect. The approach followed in these analyses is a decoupled, equivalent linear model; first the dynamic response of the potential sliding mass is computed, then the horizontal equivalent acceleration (HEA) time-history is calculated and double-integrated, with respect to time, over the time range that the HEA exceeds a given yield coefficient, k_y, to compute displacements. The maximum value of the HEA time-history (MHEA) is the seismic coefficient, k_{max}. and is part of the output of the QUAD4M analyses. Two pairs of sliding surfaces were studied as part of this project: one shallow and one deeper sliding surface on the waterside of the levee and a similar pair on the landside of the levee.

3 ANALYSIS RESULTS

Due to space limitations only results for Levee A will be presented. Results for Levees B and C are presented by Athanasopoulos-Zekkos (2008). The magnitude of the seismically induced displacements will depend on the seismic resistance of the earth embankment (k_y) and the seismic demand (k_{max}). Figure 2 shows the variation of k_{max} with PGA_{input}, for Levee A, for two of the sliding surfaces that were studied. The black solid lines are the medians, and the heavy dashed lines represent the -/+ one standard deviation ranges.

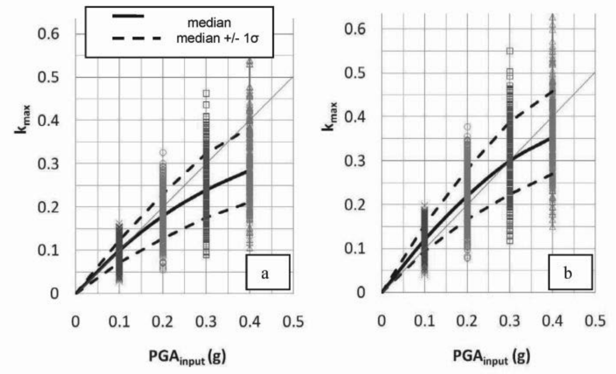

Figure 2.Results for k_{max} (MHEA/g) for the (a) deeper and (b) shallower sliding surface on the waterside of Levee A.

The seismic displacements are then computed using the USGS Java-based software (Jibson and Jibson, 2003). The yield coefficient, ky, is considered to remain constant throughout the duration of the shaking. As expected, the displacements increase as the k_y/k_{max} ratio decreases. The displacements also increase, for any given value of k_y/k_{max} ratio, with increasing PGA_{input}. This can be explained if the following is considered: when integrating the HEA time-history, even of the MHEA (i.e., k_{max}) and k_y values are the same, the higher PGA_{input} will most likely have a larger area of HEA, exceeding k_y, and being integrated over time to calculate displacements. This effect exists regardless of the M_w of the ground motions, and becomes less pronounced for PGA_{input} >0.3g, for the suite of levee cross-sections studied herein.

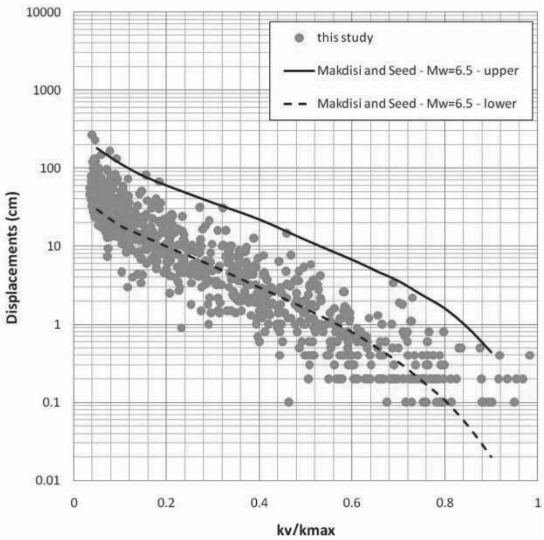

Figure 3.Seismic displacements for motions with M_w=6.5 to 7.0 and PGA_{input}=0.1g, for Levee A.

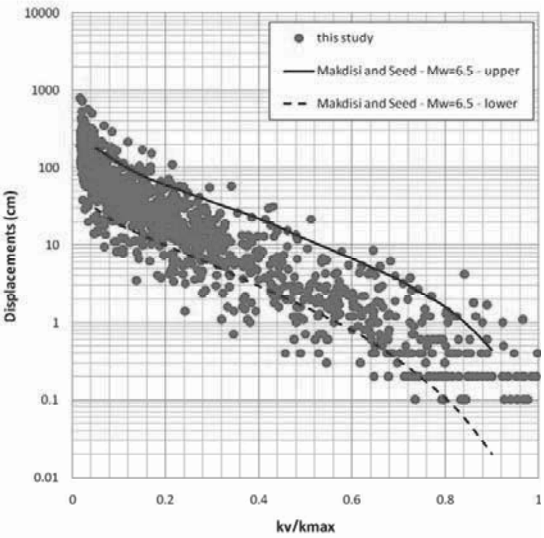

Figure 4.Seismic displacements for motions with M_w=6.5 to 7.0 and PGA_{input}=0.2g, for Levee A.

This can be further illustrated by comparing results from this study with the Makdisi and Seed (1978) displacement charts, for given M_w ranges. As Figures 3 through 6 show, for the moment magnitude bin, M_w = 6.5, the calculated displacements increase for a given k_y/k_{max} ratio, with increasing PGA_{input}.: for PGA_{input}=0.1g, the calculated average displacements plot on the lower bound of the Makdisi and Seed (1978) curves, for PGA_{input}=0.2g they plot between the two bounds, but still closer to the lower bound curve, for PGA_{input}=0.3g the displacements fall between the upper and lower bound curves, and finally for PGA_{input}=0.4g they plot closer to the upper bound. A similar pattern can be seen for the bin M_w=7.5. This provides an important insight as to how to interpret these bounds proposed by Makdisi and Seed (1978) for different shaking intensities, within the same magnitude bin.

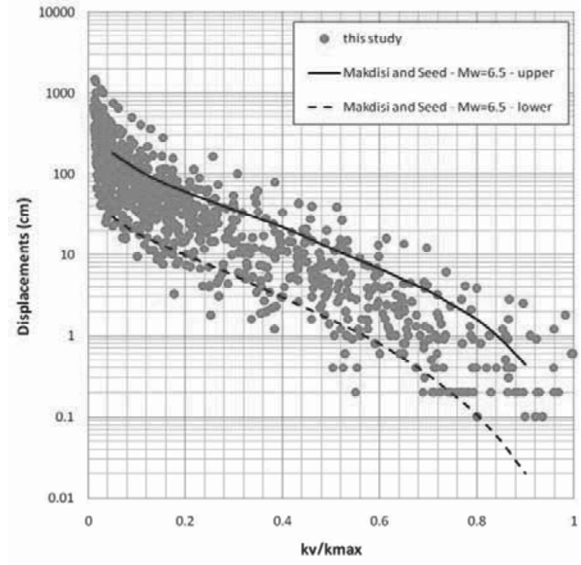

Figure 5.Seismic displacements for motions with M_w=6.5 to 7.0 and PGA_{input}=0.3g, for Levee A.

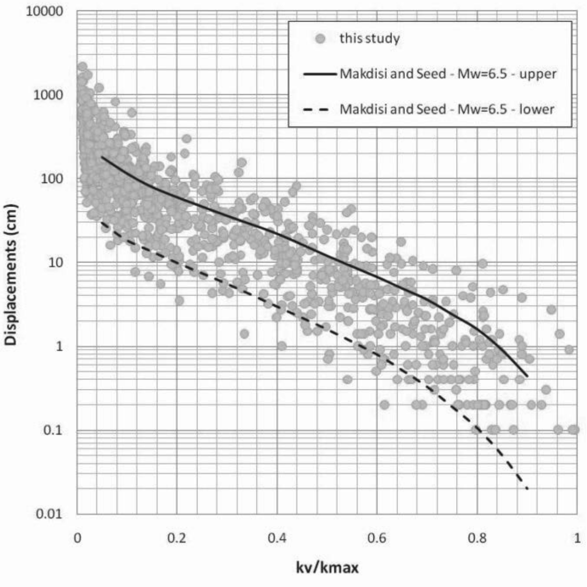

Figure 6.Seismic displacements for motions with M_w=6.5 to 7.0 and PGA_{input}=0.4g, for Levee A.

The scatter, as can be seen from the displacement plots, is significant and represents the variability of the dynamic response due to the wide range of ground motions that were used in the analyses. In an effort to reduce the scatter a group of parameters that seemed more promising were examined for normalizing the seismic displacements [i.e., peak ground acceleration (PGA_{input}), peak ground velocity (PGV_{input}), seismic demand (k_{max}), mean ground motion period (T_m), significant duration ($D_{5\text{-}95}$), arias intensity (Ia) and site period (T_s)]. Detailed results for all parameters can be found in Athanasopoulos-Zekkos (2008, 2010).

In summary, it was found that the PGV_{input} is the intensity measure that correlates the best with seismic displacements for stiff sites (T_s = 0.45 to 0.58sec) with weak slopes (k_y=0.05 to k_y=0.1). This can be explained since PGV_{input} is less sensitive to high frequencies and is also a good proxy for intensity as well as duration for short period structures, as is the case with earthen levees. PGV_{input}^2 was also examined (Newmark, 1965), but it did not give a better correlation than PGV_{input}. An additional advantage to PGV is that it can be directly estimated using the New Generation Attenuation (NGA) relationship models, for a given earthquake scenario (Boore and Atkinson, 2008, and Campell and Bozorgnia, 2008). As shown in Figure 7 the normalized seismic displacements follow a linear trend in a semi-logarithmic plot. The standard deviation for all regressions for the three levee cross sections is on average 0.3 in log units. .

After compiling the regressions for all sliding surfaces and all intensity levels the lines shown in Figure 8 are recommended for evaluating seismic displacements for the three levee cross-sections.

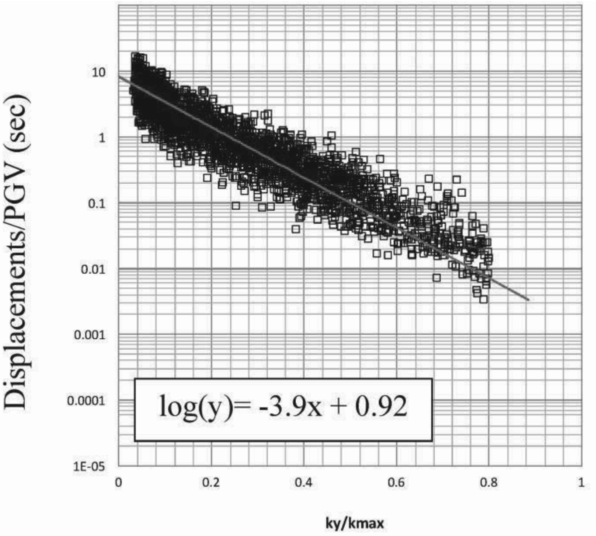

Figure 7. Normalized seismic displacement for the deeper sliding surface on the waterside of Levee A, PGA_{input}=0.2g

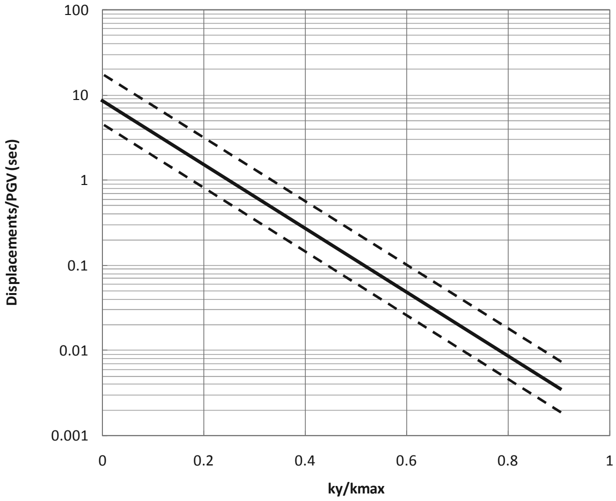

Figure 8. Recommended normalized seismic displacement lines (16%, 50% and 84% probability of exceedance) (all PGA_{input}).

4 CONCLUSIONS

Levees are very challenging engineering structures to study, in part because they are not typically well-engineered structures. Unfortunately, there is little to no guidance as to how to evaluate the seismic vulnerability of levees. This study focuses on systematically studying the dynamic response of levees and developing a simplified procedure for the evaluation of seismically induced deviatoric displacements for levees. The study was based on levee sites representative of select California Central Valley regions; however, since floodplains tend to generally have similar depositional environments, it can be extended to other regions as long as some of the principal characteristics are still applicable.

Three levee sites, with different underlying soil stratigraphy, were studied. There were differences in the dynamic response among the three sites, however these differences were smaller than the variability in response introduced by the input ground motions. A wide range of ground motions were used in an effort to capture not only the average response of levees, but also the variability and its underlying root causes.

Four critical sliding surfaces have been selected for the evaluation of permanent seismic deviatoric type displacements. The variability of the seismic coefficients for each surface was found to be related to the degraded site period, indicating that for earth embankments of small heights (~10 m), the overall site response is more important than the response of the sliding mass itself. The seismic displacements were calculated using a decoupled equivalent-linear, Newmark-type approach. The variability of the seismic displacements due to the different ground motions was also significant. It was efficiently reduced however, by normalizing the displacements with regard to the peak ground velocity (PGV) of the input ground motion. The regressions for the normalized displacements showed that PGV is both efficient and relatively sufficient in capturing the important characteristics of the ground motion, when computing seismic slope displacements. The standard deviation of the regressions is on average equal to 0.3 log units. The graph of Figure 8 is recommended for estimating normalized seismically-induced deviatoric displacements for levee sites that have similar stratigraphy and geometry to the three levees in Figure 1. This simplified procedure focuses on seismic slope stability of earthen levees, and is not recommended for other earth embankments that are vastly different from levees (i.e. dams, landfills). Since the soil materials were modeled as equivalent-linear, this procedure should not be extrapolated to PGA values larger than 0.4g.

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