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Fifth International Conference on
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VARIABILITY IN EARTHEN LEVEE SEISMIC RESPONSE DUE TO TIME-HISTORY SELECTION

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ABSTRACT

In seismic slope stability analyses the single most important input parameter is the ground motion. Time-history selection is a challenging engineering problem since the variability in ground motion characterization is in part due to the complexity of the mechanisms that result in a seismic event taking place and the path and soil conditions from the origin of the seismic event to the location of interest. In this study, the effect of key ground motion parameters to the dynamic response of earthen levees is investigated. Specifically, the effect on the induced cyclic shear stress ratio (CSR) and/or seismically induced Newmark-type, permanent displacements (U) for prescribed sliding surfaces is discussed. Results were obtained by performing 2-D equivalent linear finite element dynamic analyses for a total of 1,000 ground motions. The mean period, T_m, of the ground motion, and the peak ground velocity, PGV, are among the parameters identified by this study as being good indices for seismic levee response. Identifying the parameters that correlate best with the variability in response will allow the formulation of time-history selection criteria for the seismic response of earthen levees.

INTRODUCTION

Time-history selection is a challenging engineering problem since the variability in ground motion characterization is in part due to the complexity of the mechanisms that result in a seismic event taking place and the path and soil conditions from the origin of the seismic event to the location of interest. In seismic slope stability analyses the single most important input parameter is the ground motion (Bray, 2007). Recent studies by Athanasopoulos-Zekkos (2008) showed that the variability in seismic levee response due to the selection of a wide range of ground motions was much higher than the variability in response due to varying soil stratigraphy and levee geometry. 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. Recent studies (URS, 2007) concluded that there is approximately a 0.5% chance per year of an earthquake event occurring in Northern California that would cause more levee breaches within the Sacramento-San Joaquin River Delta than could be repaired within a 12-month time window, in time for the annual high flood water level. Levees along the Mississippi River could also be compromised due to a seismic event in the New Madrid Seismic Zone.

This paper investigates the effect of key ground motion parameters on the dynamic response of earthen levees. Specifically, the effect on the induced cyclic shear stress ratio (CSR) and/or seismically induced Newmark-type, permanent displacements (U) for prescribed sliding surfaces is discussed. Results were obtained by performing 2-D equivalent linear finite element dynamic analyses for a total of 1,000 ground motions. The author believes that by identifying these important ground motion parameters, regression models can be developed to help in the development of ground motion selection guidelines for dynamic analyses of earthen levees.

DYNAMIC ANALYSES

The dynamic analyses were performed using the computer program QUAD4M (Hudson et al. 1994). QUAD4M is a dynamic, time-domain, equivalent-linear, 2-D finite element program. QUAD4M is a modification of the original version QUAD4 (Idriss et al., 1973). As part of the modifications to the code, a transmitting base, an improved time-stepping algorithm, seismic coefficient calculations, a restart capability and a change in the algorithm by which damping is set were implemented. The transmitting base concept is important as it eliminates the need to assume a rigid foundation at the bottom of the finite element mesh used to model the engineering problem. QUAD4M also has the capability to directly calculate the seismic coefficient (k_{max}) for a given sliding surface, which is very useful for seismic displacements calculations. It also incorporates a new method for the formulation of the damping matrices, which results in a significant reduction of the over-damping of higher frequencies commonly associated with the Rayleigh damping formulation.

Levee cross-sections

The approach followed in this study is to collect information regarding the site conditions and levee geometries at various locations in Central California and then to develop 3 representative cross-sections for simplified characterization of critical levees of high flooding risk for urban areas. The three levee cross-sections that were analyzed in this study are representative of the Stockton area (Levee A), the West Sacramento area (Levee B) and the Marysville (Yuba) area (Levee C).

These three locations are among the sites currently under study as part of the Urban Levee Project, authorized and directed by the California Department of Water Resources.

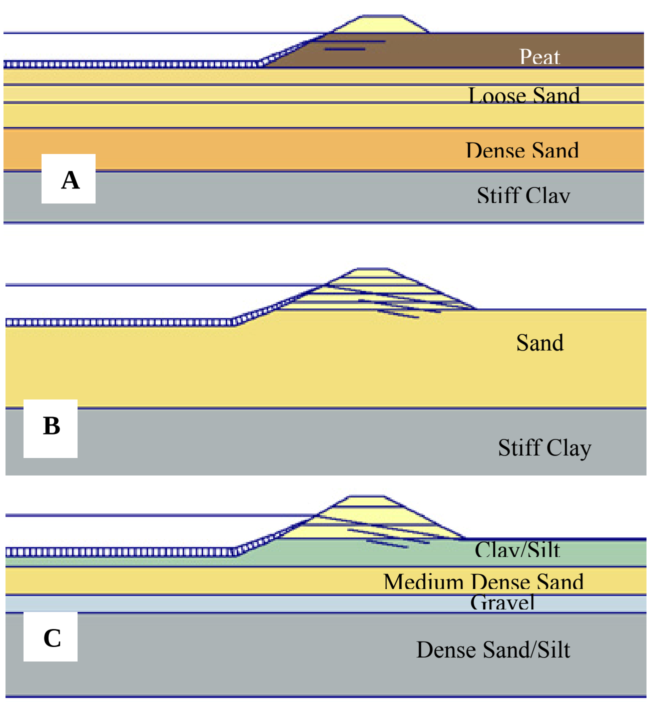

Fig. 1: Levee geometry for the three general levee cross-sections (Athanasopoulos-Zekkos, 2008)

The site subsurface conditions, and also the levee embankment geometries, are different and provide a good basis for comparisons in terms of dynamic response. The levee sites can also be considered typical and representative of levee sites in other river valleys and deltas, since the mode of deposition in these types of environments, even though complex is often similar, though locally distinct. Figure 1 shows the three earthen levee cross sections and fig. 2 presents the shear wave velocity profiles used in the analyses. The geometry and soil stratigraphy of these three cross-sections were determined after examining a compilation of the available geotechnical data for each region, provided by URS Corp., Oakland, through personal communications. These cross-sections are intended to represent typical (average) conditions at these three locations.

The mesh should be extended laterally, until free-field conditions are achieved and the wave reflections from the side boundaries are minimized. The finite element mesh geometries were varied with regard to the locations of the side boundaries, and the results showed that extending laterally the mesh four times the average width of the levee on each side was sufficient for providing an approximately infinite field condition.

The depth to the transmitting base for the three levee cross-sections that were studied was determined based on the studies performed by URS for the Delta Risk Management Strategy Project (URS, 2008) and for the Urban Levee Geotechnical Evaluations (Scott Shewbridge, 2008, personal communication). Generally, it is preferred to establish a clear boundary indicated by a high impedance ratio resulting from a change in the shear wave velocity between two layers. This is relatively straightforward when bedrock, or some form of rock or very stiff soil is encountered at some depth. In this case however, due to the depositional environment of the Central California Valley, the soil deposits extend for many hundreds of feet, stiffening progressively with increased depth making it impractical to extend the finite mesh all the way to "bedrock". Instead, it was decided to cut off the finite mesh at the depth where the soil deposits reach a shear wave velocity of 1200 ft/sec, and to model a half-space below that depth. In all three cases this meant including the upper layers of the Pleistocene deposits.

The water elevation on the channel side varies seasonally throughout the year, from only a few feet above mean sea level (MSL) to almost the levee crest elevation during high annual water levels at certain locations. The change in water elevation will mostly affect calculations of static slope stability that include through seepage and/or underseepage flow, and is considered to be a secondary issue for the dynamic response analysis calculations, as performed in this study. For this study, the water elevation is taken equal to the annual normal elevation, which is at approximately +10 to +12 feet MSL, and is held constant throughout the analyses.

Dynamic Soil properties

For the dynamic analyses performed in this study the required input soil properties include the Maximum or Small-Strain Shear Modulus, G_{max}, the Shear Modulus Reduction, G/G_{max} as a function of shear strain, the material Damping Ratio (%) as a function of shear strain, the Unit Weight, γ, and the Poisson's Ratio, ν. The G_{max} was computed using equation 1:

$$G_{max}=\rho * V_s^2 \tag{1}$$

Where ρ is the density of the soil and V_s is the shear wave velocity.

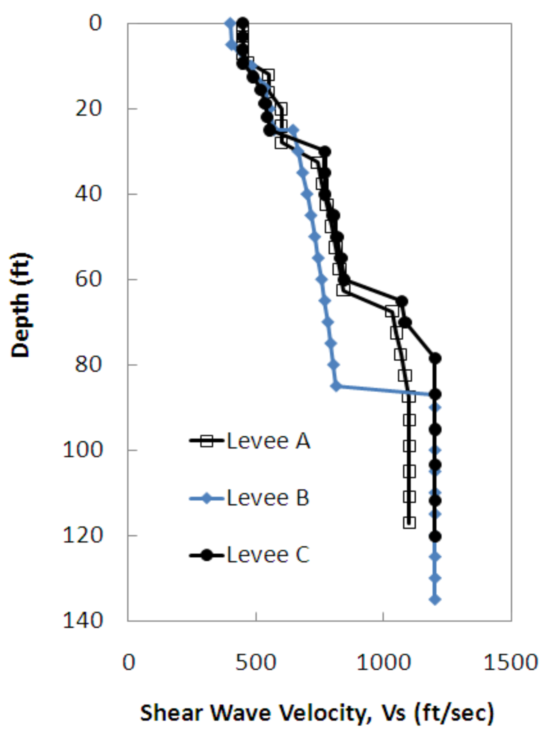

Fig. 2: Shear wave velocity profiles for the three general levee cross-sections (Athanasopoulos-Zekkos, 2008)

Typical values of unit weight and Poisson's ratio were used for all soils. For the sandy soils, the Seed and Idriss (1970) average G/G_{max} and damping curves were used, whereas when the fines content (FC) of the sandy materials was >5%, the upper bound G/G_{max} curve and the lower bound damping curves were used. The same curve was used for the deep sand deposits, since it agrees well with the Darendeli (2001) curve for σ'_c=1atm. For the clayey soils, the Vucetic and Dobry (1991) curve for PI = 30 was used. The Rollins et al. (1998) average curve was used for the gravelly soils. Shear modulus reduction and damping ratio curves for peats and organic materials have been developed based on laboratory testing of samples retrieved at specific sites, rendering these curves rather site-specific. Wehling et al. (1998) performed a series of laboratory tests on samples retrieved from the Sacramento Delta area (Sherman Island), and Kishida et al. (2009) developed G/G_{max} reduction curves and damping ratio curves for soil samples of the Montezuma Slough. However, the marsh deposits found in Levee A, are different from these tested soils in that they have much less fibers and have higher shear wave velocity values. When testing municipal solid waste, Zekkos et al. (2008) showed that when reducing the fiber content and increasing the non-fibrous material, the shear modulus reduction curve moved to the left, towards significantly smaller shear strains. Therefore, the Vucetic and Dobry (1991) curve for fine-grained soils of PI=30 was used, that falls to the left of the Kishida et al. (2009) and Wehling et al. (1998) proposed curves.

Input Ground Motions

A wide range of ground motions were used in these studies 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 and satisfied the following criteria:

1) Moment magnitude (M_w) = 5.5 to 7.7
2) Distance of site of recording from epicenter (EpiD) = 20 to 110 km
3) Preferred $V_{s,30}$ >180 m/sec (~600 ft/sec)
4) Peak Ground Velocity (PGV) < 100 cm/sec and Peak Ground Displacement (PGD) < 100 cm

Additionally, the number of records from the Chi-Chi, Taiwan 1999 earthquake was reduced so that they did not exceed 40% of the total number of records used for the analysis of each site. The horizontal component with the largest PGA was used in the analyses.

The analyses in this study were performed for four different PGA_{input} levels: 0.1g, 0.2g, 0.3g and 0.4g. In order to match the PGA_{input}, the recordings were scaled using scaling factors within a range of 0.5 to 2. Since the PGA_{input} is less than or equal to 0.4g, an equivalent-linear soil model can be used for the dynamic analyses. Soil behavior becomes highly non-linear for PGA larger than 0.4g and the equivalent-linear procedure may not be suitably applicable. A list of all ground motions used in the analyses can be found in Athanasopoulos-Zekkos (2008).

DYNAMIC ANALYSES RESULTS

Two aspects of the dynamic response of earthen levees are presented and discussed in this paper: triggering of soil liquefaction and the seismically induced permanent displacements.

Liquefaction triggering

One of the two principal seismic hazards for levees is soil liquefaction. Once a soil layer that is susceptible to liquefaction has been identified, the Cyclic Stress Ratio (CSR) needs to be computed, and then compared to the available resistance (CRR) to determine whether liquefaction will trigger or not. The CSR_{eq} is defined as the equivalent cyclic shear stress normalized by the in-situ vertical effective stress, and the equivalent cyclic shear stress (τ_{eq}) is computed as 65% of the maximum shear stress for each element, as computed by QUAD4M. To reduce computational time, the shear stresses were computed at select vertical sections, as shown in fig. 3.

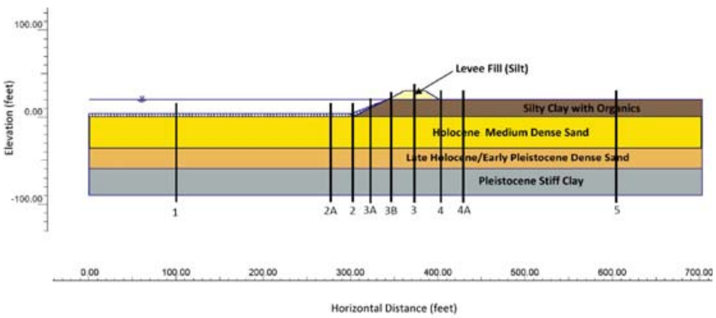

Fig. 3: Locations of computed Equivalent Cyclic Stress Ratio (CSR_{eq}) profiles for Levee A.

QUAD4M computes the maximum shear stresses for each element, but it does not compute the initial static vertical effective stresses that are needed to calculate the CSR. These initial static stress calculations were performed using the finite element code PLAXIS (Brinkgreve, 2002). The staged construction option was used to compute the stresses because of sloping ground. The cyclic shear stresses were computed at the select vertical sections, and then normalized by the in-situ vertical effective stress, to produce calculated values of equivalent cyclic stress ratio (CSR_{eq}) for all ground motions, for all PGA_{input} levels and for all levee cross-sections. The overall results can be presented in the form of contour charts to give a more complete picture of how the CSR_{eq} values change, not only with depth, but spatially as well. Figure 4 shows an example of these results for Levee A, for a PGA_{input}=0.2g. The complete results for the three levee cross-sections can be found in Athanasopoulos-Zekkos (2008).

These results represent median values of a rather large distribution of dynamic response. Figure 5 shows CSR_{eq} values as computed at one vertical location for Levee A, for ground motions scaled to a PGA_{input}=0.2g. The variability in the CSR_{eq} values comes mainly from the variability in the

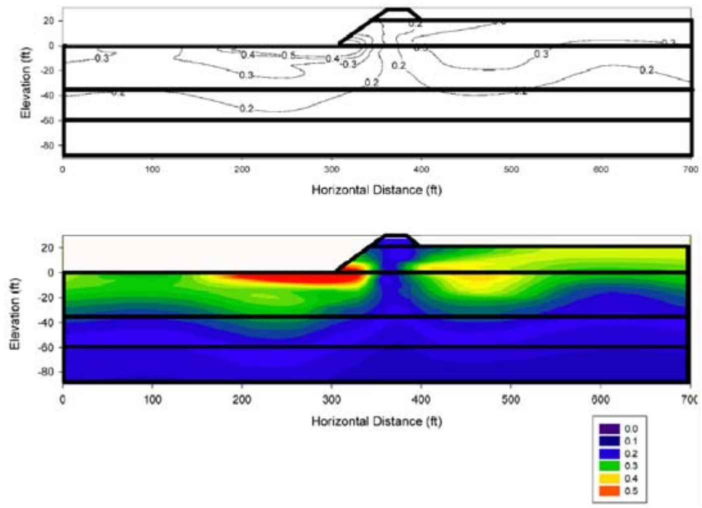

Fig. 4: CSR_{eq} contours for Levee A; PGA_{input}=0.2g (Athanasopoulos-Zekkos, 2008)

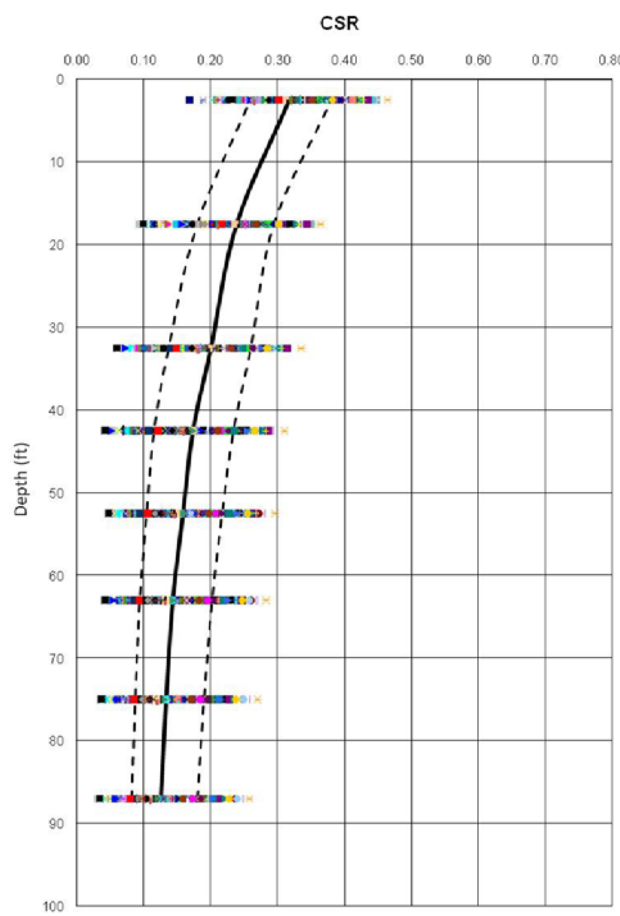

Fig. 5: CSR_{eq} profile with depth: Levee A, PGA_{input}=0.2g, location 2 (Athanasopoulos-Zekkos, 2008).

ground motions and the CSR_{eq} values for a given depth and location follow a normal distribution. The variability in response was compared to five ground motion parameters of the time-history recordings that were used in the analyses. The

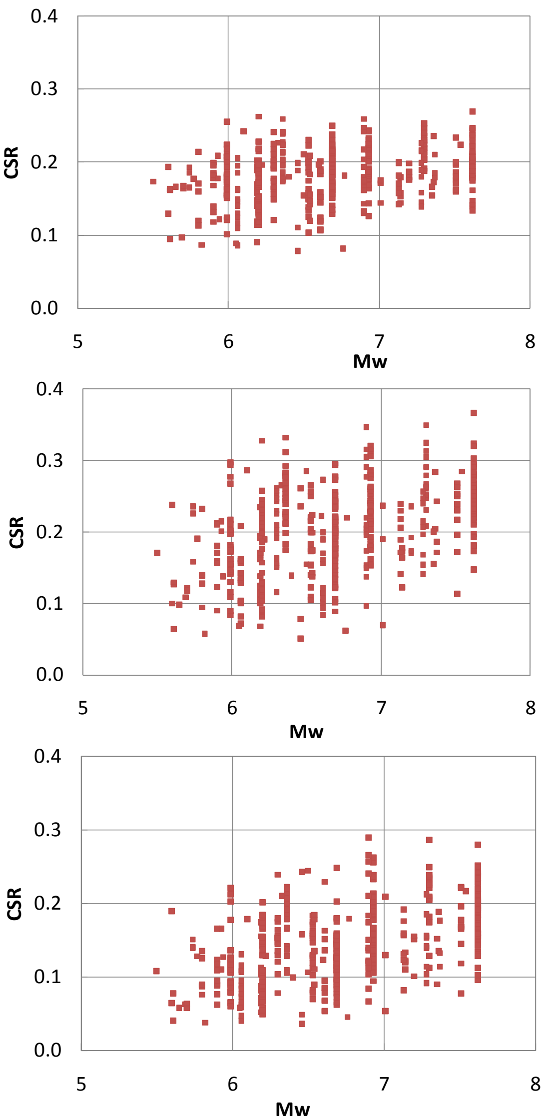

Fig. 6: Variability of CSR response vs. Moment Magnitude (Mw).

five parameters were: the moment magnitude (M_w), the significant duration ($D_{5\text{-}95}$) (Trifunac and Brady, 1975), the spectral acceleration at the site period (S_a @ $T=T_s$), the spectral acceleration at the degraded site period (S_a @ $T=1.5*T_s$), and the mean period of the ground motion, (T_m) (Rathje, et al. 1998). Figures 6 through 10 present the results for Levee A at three different depths that correspond to three different soil units, the peat layer at 20ft, the sand layer at 50ft and the dense sand at 70ft. By looking at the results, the ground motion parameter that is more strongly correlated to the variability in CSR is the mean period of the ground motion. This correlation is stronger for the deeper layers since the T_m has not changed significantly due to the ground motion propagation through the soil profile.

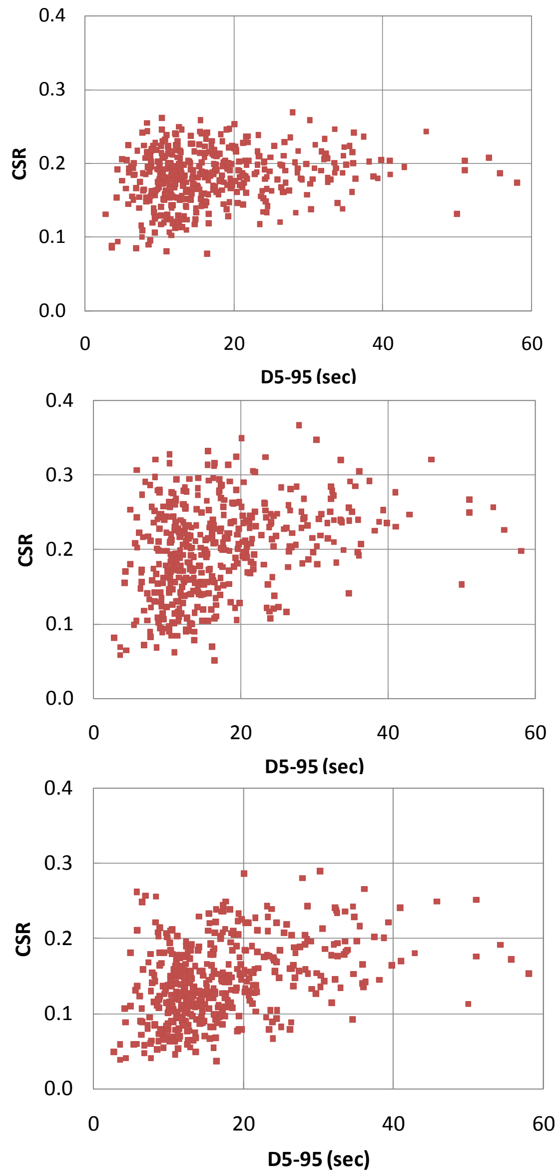

Fig. 7: Variability of CSR response vs. Significant Duration ($D_{5\text{-}95}$).

Seismic Displacements

Seismically induced deviatoric displacements have been computed using a Newmark-type approach (Newmark, 1965). The potential sliding mass is not considered to be a rigid body as the Newmark method suggests, however. 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. A decoupled, equivalent

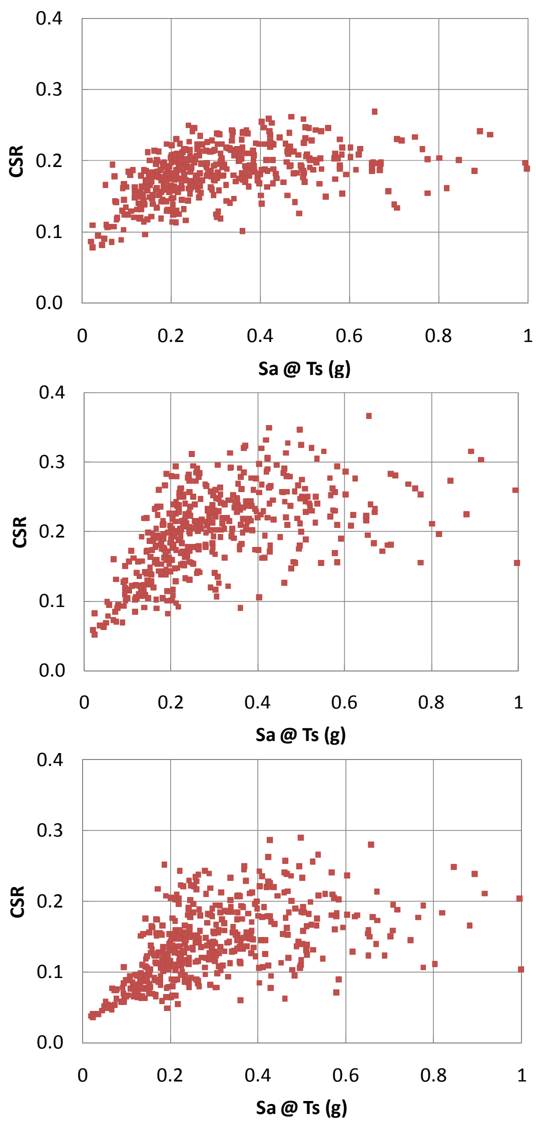

Fig. 8: Variability of CSR response vs. Sa at the site period (T_s).

linear approach is implemented; 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}. The HEA time-histories and MHEA values for a prescribed sliding surface are part of the output of the QUAD4M analyses.

A wide range of static slope stability analyses, for levee cross-sections similar to the ones presented in this study, have been performed as part of the Delta Risk Management Strategy Project (URS, 2007), for the Department of Water Resources

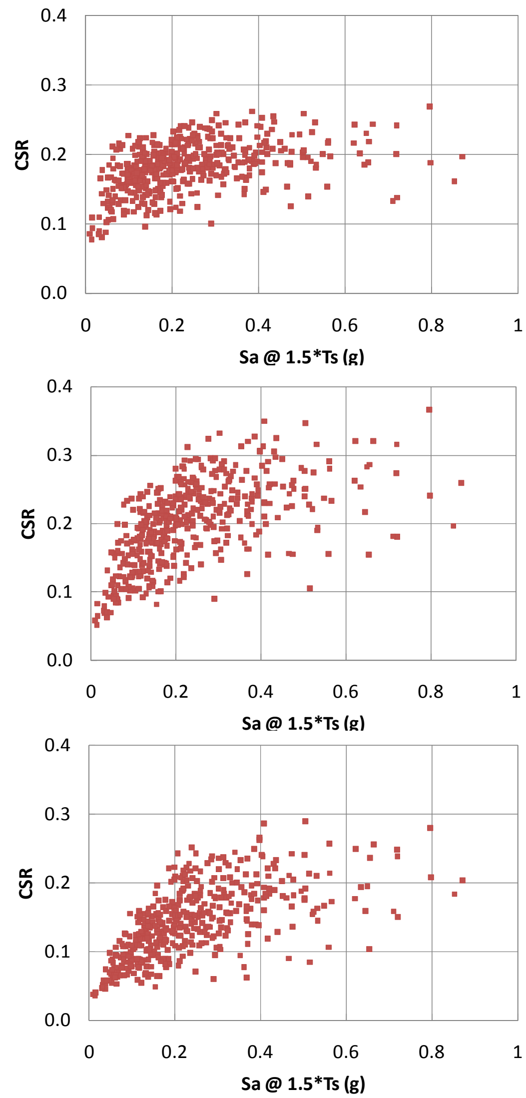

Fig. 9: Variability of CSR response vs. Sa at the Degraded Site period ($1.5*T_s$).

(DWR) in CA. These analyses showed that for static conditions the most critical failure surfaces were deeper surfaces, going through the foundation soils of the levee. The pseudostatic analyses that were performed for the same levee sites, however, indicated shallower surfaces passing through or just below the base of the levee fill as often being the most critical ones during dynamic loading. Two pairs of sliding surfaces have been studied as part of this project: one shallow and one deeper sliding surface on the waterside of the levee and a similar pair (shallow and deep) on the landside of the levee. This will allow a comparison of response between shallower and deeper surfaces for small earth structures like levees.

The seismic displacements are then computed using the USGS Java-based software (Jibson and Jibson, 2003). This code uses the input acceleration time-history, or in this case, the horizontal equivalent acceleration time-history as computed by QUAD4M for the four different sliding surfaces, and double-integrates with respect to time, when the HEA exceeds the specified k_y value. These displacements are then plotted against the k_y/k_{max} ratio, as originally proposed by Makdisi and Seed (1975). The USGS code has a precision of 0.1 cm

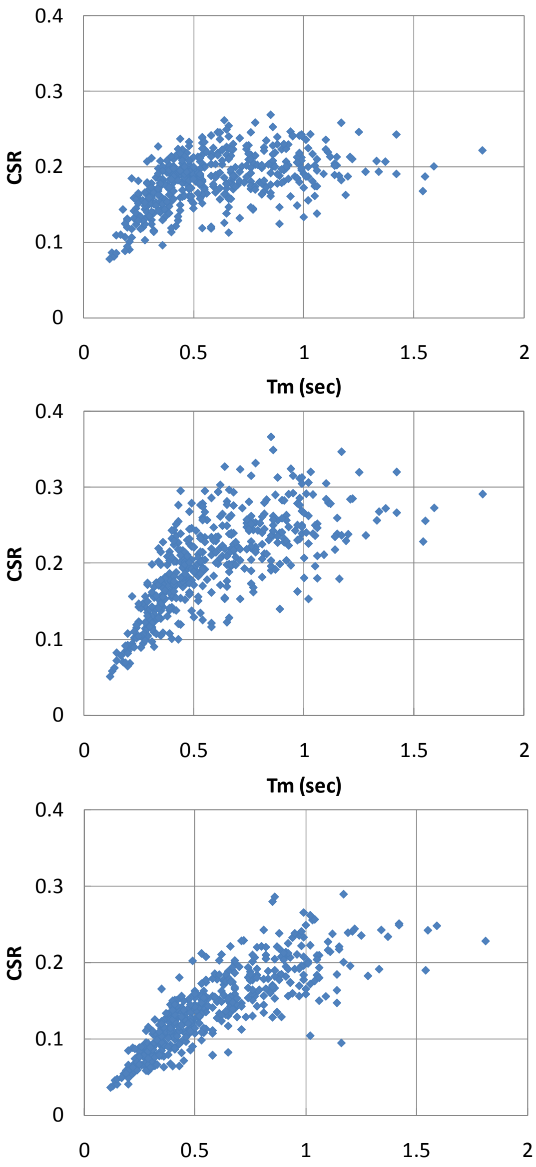

Fig. 10: variability of CSR response vs. mean period (T_m).

when calculating displacements. Displacements that are smaller or equal to 0.1 cm will all plot together as being equal to 0.1 cm. The results for Levee C are shown in fig. 11. The complete results for the three levee cross-sections can be found in Athanasopoulos-Zekkos (2008).

The scatter, as can be seen from the 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, and obtain a better predictor of the response, one needs to understand which ground motion parameters most greatly affect the response in a systematic way. Several parameters have been identified as important in the literature (e.g. Bray and Rathje, 1998, Travasarou and Bray 2003, Bray and Travasarou, 2007).

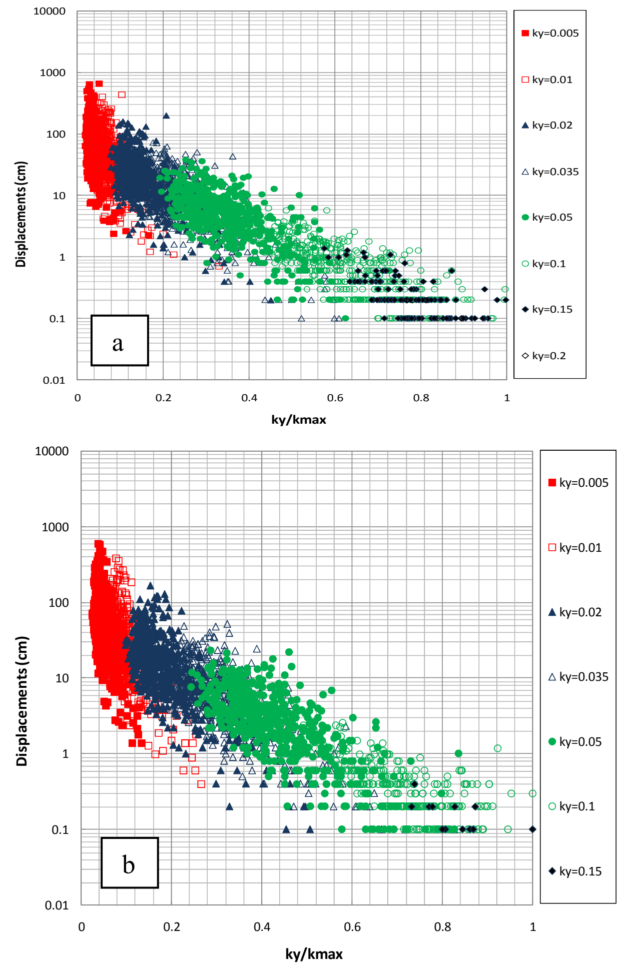

Fig. 11: Permanent seismic displacements for Levee C: a) deep sliding surface and b) shallow sliding surface (Athanasopoulos-Zekkos, 2008)

A smaller group of parameters that seemed more promising were examined for this study (i.e., peak ground acceleration (PGA_{input}), peak ground velocity (PGV_{input}), seismic demand (k_{max}), mean ground motion period (T_m) (Rathje, et al. 1998), significant duration ($D_{5\text{-}95}$) (Trifunac and Brady, 1975), arias intensity (I_a) and site period (T_s)). Figures 12 through 15 show the correlation of seismic displacements with Arias Intensity (I_a), spectral acceleration at the site period, T_s, spectral acceleration at the degraded site period, $T=1.5*T_s$, Peak

Ground Velocity (PGV_{input}), Significant Duration ($D_{5\text{-}95}$) and the product of k_{max}*$D_{5\text{-}95}$. It can be observed 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).

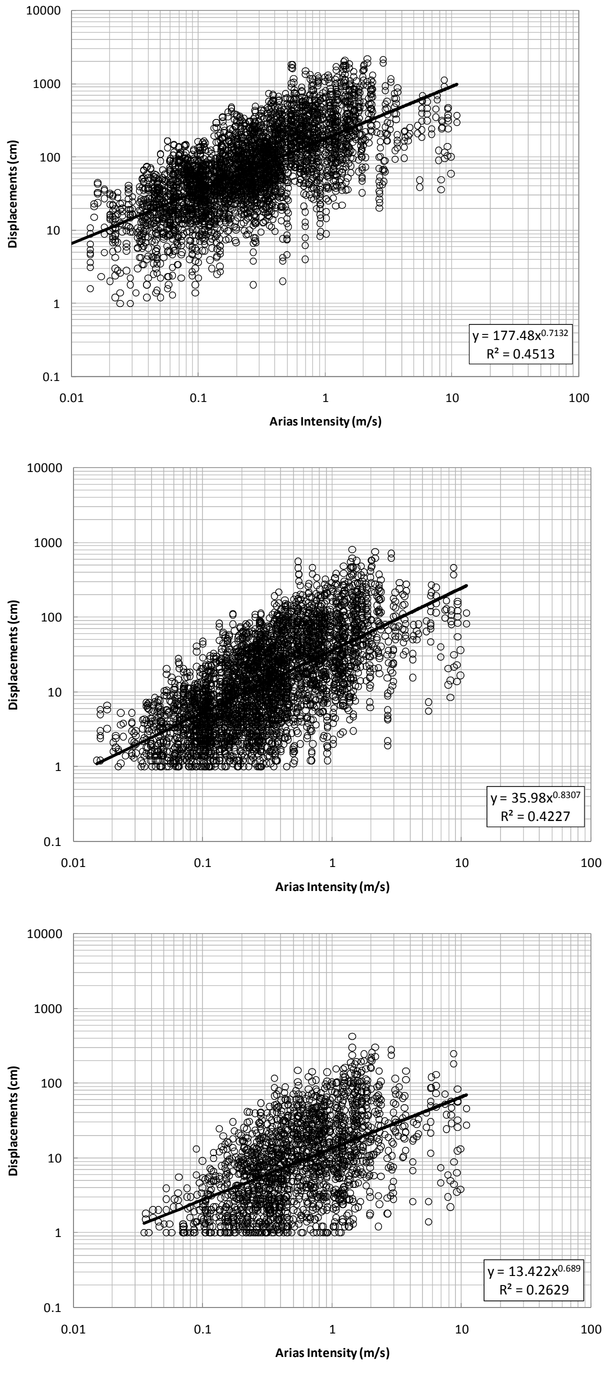

Fig. 12: Computed seismic displacements plotted vs. Arias Intensity (Ia).

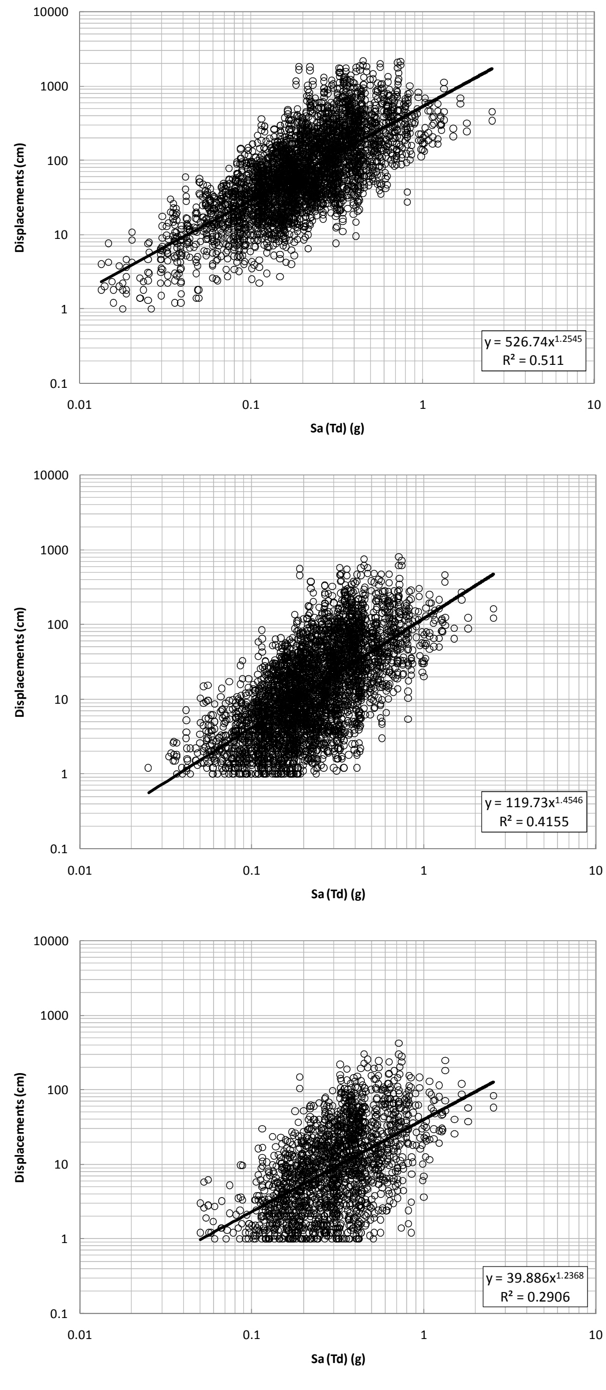

*Fig. 13: Computed seismic displacements plotted vs. Sa at site degraded period (1.5*Ts)*

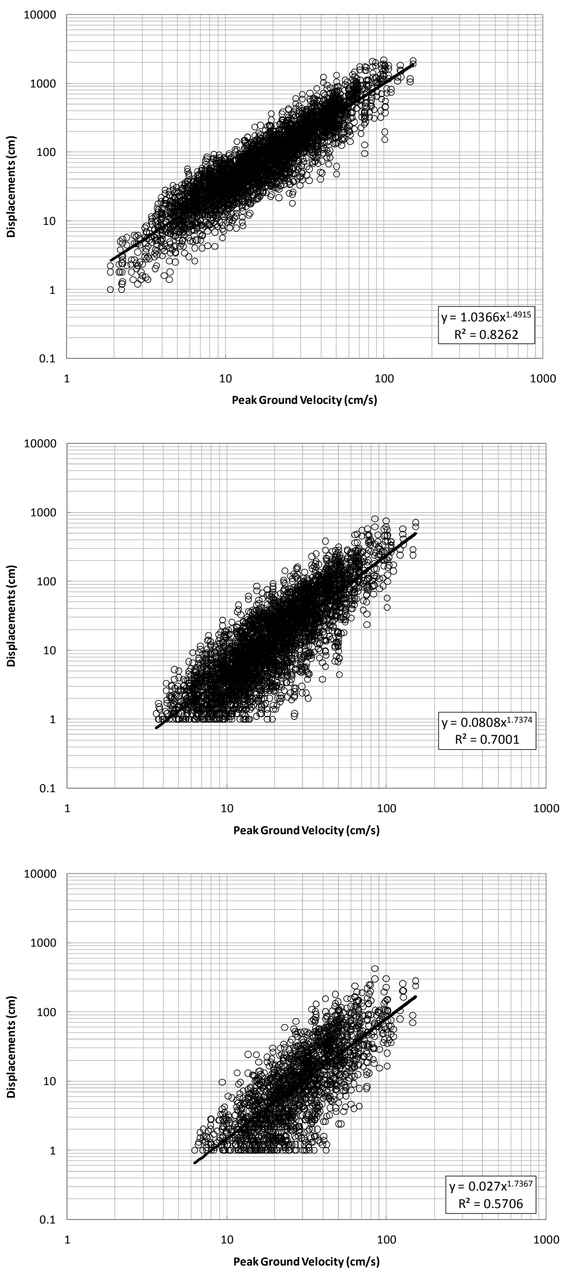

Fig. 14: Computed seismic displacements plotted vs. PGV.

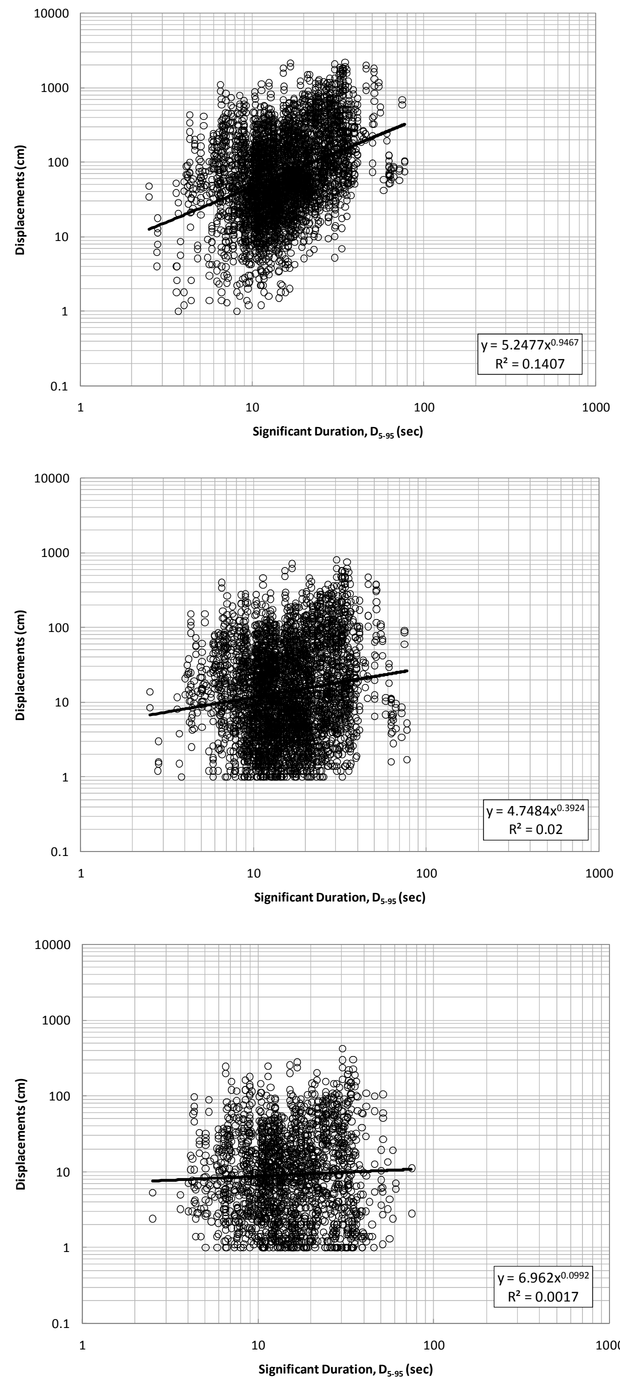

Fig. 15: Computed seismic displacements plotted vs. Significant Duration ($D_{5\text{-}95}$).

CONCLUSIONS

The selection of the input ground motion in dynamic analyses is very critical. By using large numbers of ground motions the average response as well as the variability can be evaluated. However, in common engineering practice a small number (preferably seven) of acceleration time-histories are typically used to study the seismic response of earth structures. It is therefore difficult to capture the average response and the variability without understanding what controls it.

Results from equivalent-linear dynamic analyses of three earthen levee cross-sections were analyzed with regard to the variability in levee response due to time-series selection.

For the liquefaction triggering evaluation, the mean period of the ground motion (T_m) is better correlated to the cyclic stress ratio (CSR), and specifically the computed CSR tends to be higher when a ground motion with a higher mean period is selected. The second best correlation is observed with the spectral acceleration at the degraded site period (S_a at $1.5*T_s$), where again the computed CSR tends to be higher when the S_a at $1.5*T_s$ is higher.

For the permanent Newmark-type seismic displacements, the Peak Ground Velocity is the intensity measure that correlates the best, particularly for stiff sites (T_s = 0.45 to 0.58sec) with weak slopes (k_y=0.05 to k_y=0.1).

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