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MEASUREMENTS OF TRANSLATIONAL AND ROTATIONAL DYNAMIC STIFFNESS FOR A MODEL LEVEE ON PEAT

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Abstract: An eccentric mass shaker mounted to the crest of a model levee resting on very soft peat soil was used to measure dynamic base shear-displacement and base moment-rotation relations. The model levee rotated and translated visibly during testing, exhibiting a response that deviates significantly from the one-dimensional wave propagation assumption often used to analyze the seismic response of levees. We evaluate complex-valued stiffness and damping of the levee-foundation soil interaction for translational and rotational modes of vibration. The damping is strongly dependent on frequency, indicating that it is controlled by radiation of energy away from the vibrating levee. These radiation damping effects are dominant even at low frequencies that are well within the range of engineering interest for ground failure evaluations. Interestingly, the levels of radiation damping are roughly comparable, when expressed as percentage of critical, to predictions from classical models for impedance functions of rigid rectangular foundations on an elastic half-space. More research is needed to generalize these observations for application to seismic analysis of levees resting on peat.

1. INTRODUCTION

The seismic response of levees is a crucial issue for flood control and water distribution systems. Levees are often founded atop soft soils that have the potential to perform poorly during earthquakes. Peat is the softest and most compressible type of soil on which levees are founded, but very little is known about its seismic performance. Levees resting atop peat have been observed to fail during past earthquakes (e.g., Sasaki 2009), but it is often difficult to separate the contribution of the peat from the contribution of other problematic soils such as liquefiable sands.

Seismic stability of levees is a particularly important issue in the Sacramento / San Joaquin Delta, which is the hub of California's water distribution system. Unlike typical flood control levees that are intermittently loaded, the Delta levees constantly convey water and protect land that is below sea level due to subsidence of peaty organic soil. A recent seismic risk analysis predicts that a moderate earthquake in the region would simultaneously breach many levees, thereby flooding multiple islands and drawing saline water from the bay (DRMS 2009). This event is projected to halt water delivery for a period of years, causing tens of billions of dollars in direct losses. A significant limitation for this type of loss estimation analysis is lack of knowledge regarding the seismic response of peaty organic soils.

This paper presents results from a large-scale field test of a model levee resting atop very soft and compressible peat. An eccentric mass shaker imposed earthquake-level motions on the levee, and the response was recorded using dense sensor arrays. This paper focuses on the seismic interaction between the soft peat and the comparatively stiff levee fills using soil-structure interaction concepts.

2. MODEL CONFIGURATION

A photo of the model levee and eccentric mass shaker is shown in Fig. 1. The model levee was composed of compacted clay reinforced with geogrids. The levee was

Figure 1. Model levee with MK-15 eccentric mass shaker mounted on crest.

1.8m tall, 12m long at the base (from left-to-right in Fig. 1), and 3.7m wide. The clay was compacted in six 0.3m thick lifts that were wrapped with geogrid to form vertical side walls, thereby modeling a slice of levee. A sturdy timber frame was embedded in the upper three lifts, and the nees@UCLA MK-15 eccentric mass shaker was attached to the frame.

The model levee was constructed on the interior of Sherman Island, near Antioch, CA. Deposition of the peat began about 11,000 years ago at the end of the last ice age. Following reclamation of Delta lands beginning in 1850, the peat has subsided at a rate as high as 10 cm/year, and many islands now lie more than 5m below sea level. The soil profile beneath the model levee consisted of 2m of unsaturated desiccated peat overlying 9m of soft fibrous peat overlying a deposit of Pleistocene dune sand (Fig. 2). The saturated fibrous peat exhibited water contents as high as 500%, and shear wave velocities near 25 m/s. At a depth of 2m, the peat is nearly entirely organic, with very little visible evidence of inorganic minerals, with increasing content of inorganic clay minerals deeper in the deposit. Details of the laboratory testing program that accompanies the test can be found in Shafiee et al. (2013).

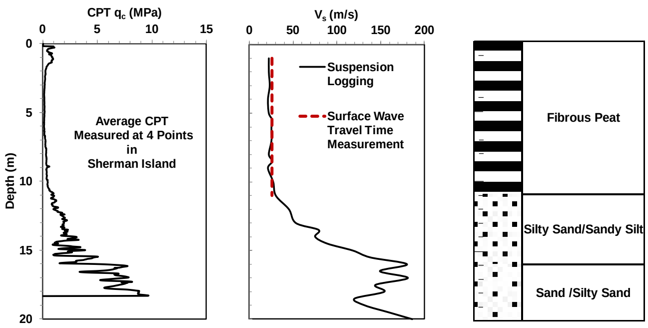

Figure 2. Cone tip resistance and shear wave velocity profiles for free-field Sherman Island site (Shafiee et al. 2013). Suspension log conducted by GeoVision (2000) at a similar site near the test site.

3. DATA PROCESSING AND ANALYSIS

This section explains the procedures used to calculate the base shear, base moment, average base displacement, and average base rotation of the model test levee for the purpose of defining the stiffness and damping of levee-foundation soil interaction. A schematic of the levee and the accelerometers used to calculate these values can be seen in Fig. 3. Eight EpiSensor triaxial accelerometers were placed on each side of the embankment: four along the base, two at mid-height, and two on the crest. Sixteen total accelerometers were mounted on the levee (eight on each side) and additional accelerometers were placed on the ground surface away from the levee, and subsurface accelerometers and piezometers were placed in the peat beneath the levee, though these sensors are beyond the scope of the paper. The embankment was then divided into sixteen tributary wedges, and the centroid, volume, and weight of each wedge was calculated. The test data used to calculate desired quantities consisted of the x and z components of acceleration of the accelerometers on the embankment and the shaker force F_{shk} [see Reinert et al. (2012) for details on F_{shk} calculation].

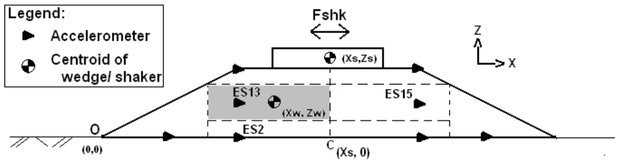

Figure 3. Schematic of model levee including shaker and instrumentation.

The first step was interpolating acceleration at the centroid of each wedge from the measured accelerations. For example, consider the shaded wedge in Fig. 3. The z-component of acceleration at the centroid was interpolated between ES13 and ES15 since vertical acceleration is anticipated to vary horizontally due to rotation of the levee. The x-component of acceleration was taken as being equal to ES13 in this case since the elevation of the centroid is equal to the elevation of ES13. For some wedges, the elevation of the centroid is not identical to the elevation of any accelerometer, in which case the centroid acceleration is interpolated vertically between the nearest two sensors.

Once the representative accelerations for each wedge were computed, we then calculated the base shear and moment of the embankment by (*i*) computing inertia force for each wedge in the horizontal and vertical directions, (*ii*) summing horizontal inertia forces plus shaker force to obtain base shear, and (*iii*) summing horizontal inertia force multiplied by vertical moment arm, vertical inertia force multiplied by horizontal moment arm, and shaker force multiplied by the height to the centroid of the shaker. Moments were computed about the center of the base [i.e., at point (x_s,0) in Fig. 3]. Shear is positive from left-to-right, and moment is positive clockwise. Steps (ii) and (iii) are explicitly defined in Eqs. 1 and 2.

$$V_{base} = F_{shk} + \sum_{i=1}^{16} -m_i a_{x,i} \tag{1}$$

$$M_{base} = z_s \cdot F_{shk} + \sum_{i=1}^{16} -m_i a_{x,i} z_{w,i} + \sum_{i=1}^{16} m_i a_{z,i} (x_{w,i} - x_s) \tag{2}$$

The final step of calculations was to compute a representative base displacement and rotation, which are combined with the shear and moment to evaluate frequency-dependent stiffness. First, displacements were computed by double-integrating the acceleration records in time. The Fourier transform of each record was computed, and the real and imaginary components were multiplied by a Butterworth filter with an order of 5 and a corner frequency of 0.2 Hz. Note that this filter is acausal (i.e., it does not alter the phase of the signals) since the real and imaginary components are both multiplied by the same scalar. The filter was required to remove low frequency noise that would otherwise cause erroneous drift in the displacement records. The representative base displacement was then computed as the average of the x-component of displacement from the eight accelerometers along the base of the levee. Very little variation in these motions was observed, and an equally-weighted average is therefore reasonable.

The representative rotation is complicated by flexibility of the model levee. Fig. 4 shows undeformed and deformed positions of the accelerometers during positive and negative loading cycles. The base of the levee is clearly nonlinear, which indicates that the rotation varies along the length of the levee. The representative rotation in this case was computed using a weighted least squares regression approach in which the weights for the two sensors nearest to the center of the levee were three times larger than the weights of the sensors nearest to the toes of the levee slopes. The motivation for using a weighted least squares procedure is that more mass lies near the center of the levee, therefore the rotation near the center should be more representative of the flexible levee response.

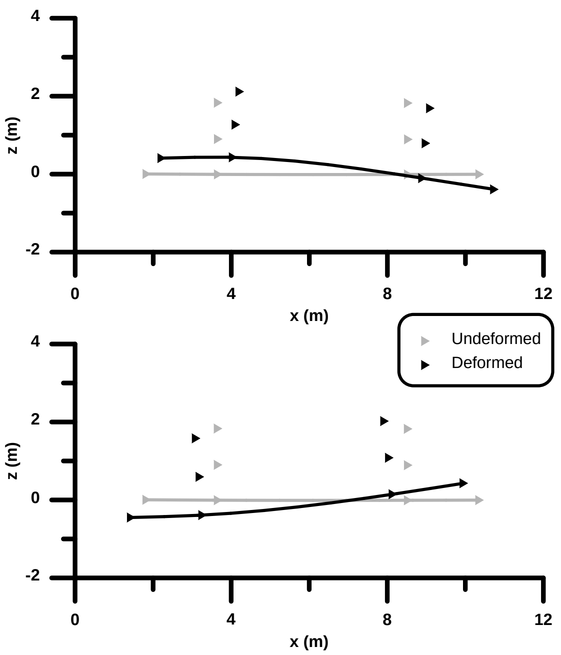

Figure 4. Deformed and undeformed displaced positions of sensors during a positive and negative loading cycle (displacements amplified $\times 100$).

4. MEASURED SHEAR-DISPLACEMENT AND MOMENT-ROTATION RESPONSES

Measured levee-foundation soil responses are presented in Figs. 5 and 6 in terms of base shear versus horizontal translation and base moment versus representative rotation. The results in Fig. 5 apply for a medium intensity motion that resulted in a maximum horizontal crest acceleration of 0.04g. At 1Hz, the moment-rotation relation is essentially linear with no measurable damping, while the horizontal force-displacement relation exhibits a small amount of damping. Radiation damping and hysteretic damping are likely present in the measurement, though separating the relative contribution of each is not possible from the measured data. As the frequency increases, the damping increases as well, and the force-displacement curves are essentially circular at 3Hz. Damping also increases for moment-rotation, but not as significantly as for force-displacement. This trend was also observed by Tileylioglu et al. (2011) for a rigid concrete foundation on stiff soil.

Fig. 6 presents the measured responses for a high intensity motion that resulted in a maximum crest acceleration of 0.27g. The curves for f=3Hz are not presented because the shaker capacity was mobilized during this motion, and could not reach frequencies higher than 2.6Hz. For a given frequency, more damping is apparent in the responses for the high intensity motion compared with the medium motion. This trend is likely the result of higher shear strains mobilized in the soil by the high intensity motion, which would cause (i) increased hysteretic damping, and (ii) increased radiation damping due to the reduction in shear modulus (and reduction of equivalent shear wave velocity) of the peat and associated increase in dimensionless frequency, $a_o = \omega B/V_s$, where ω = angular frequency = $2\pi f$, and B = footing half-width. The non-harmonic features in the shear-translation and moment-rotation responses for the higher frequency motions were caused by pounding between the timber frame and the model levee.

The dramatic increase in damping with frequency is consistent with analytical solutions for rigid footings on an elastic halfspace. For example, consider B = 1.85m, V_s = 25m/s, and f = 3Hz. The dimensionless frequency is $a_o = 2\pi(3\text{Hz})(1.85\text{m})/(25\text{m/s}) = 1.4$. The radiation damping for a rigid rectangular footing with L/B = 12m/3.7m = 3.2 is 86% for translation and 108% for rotation using the solutions suggested by Pais and Kausel (1988). These very high radiation damping values at low frequencies are caused by the peat's extraordinarily low shear wave velocity.

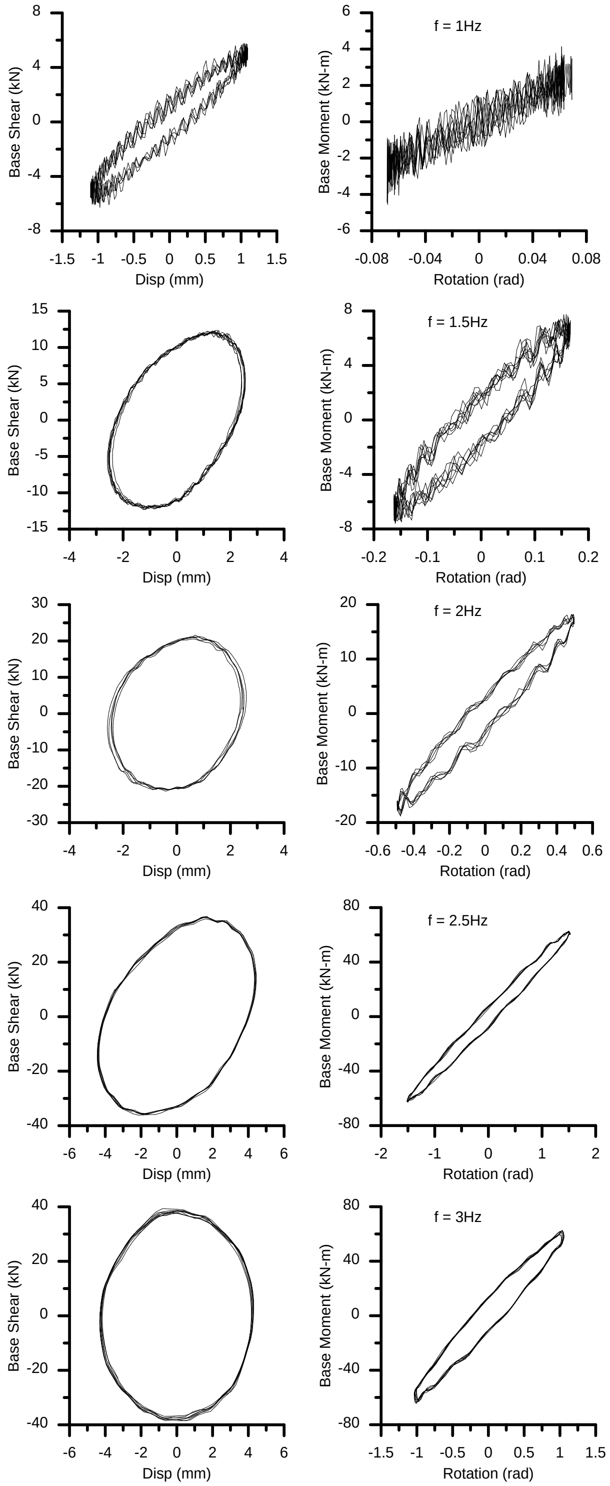

Figure 5. Impedance relations for a medium intensity motion that resulted in peak horizontal crest acceleration of 0.04g.

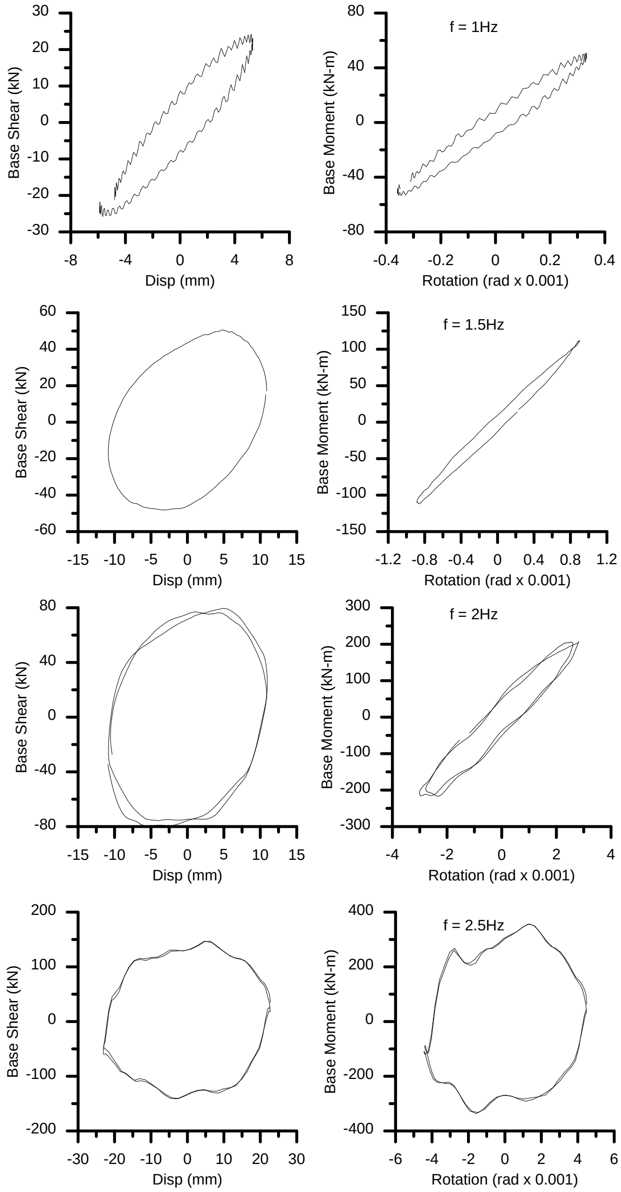

Figure 6. Impedance relations for a large intensity motion that resulted in peak horizontal crest acceleration of 0.27g.

4. CONCLUSIONS

A dynamic test of a model levee on very soft peat soil was interpreted herein using soil-structure interaction concepts. This approach is reasonable because the levee fill is significantly stiffer than the underlying peat, which had a shear wave velocity of only 25m/s. Measurements of V_s for the levee fill have not yet been processed, but we anticipate that V_s was at least 150 m/s based on visual/manual observations of the unsaturated clay fill. The model levee translated and rotated significantly during shaking. The response of the levee indicates that seismic analysis of levees using one-dimensional wave propagation theory may be inappropriate when the foundation conditions are very soft. For example, a one-dimensional site response analysis of a profile below the levee crest could not possibly capture the rotational response, and may result in erroneous prediction of crest acceleration. Furthermore, rotational deformation of the levee causes rotations of principal shear stresses, resulting in a stress path that is different from simple shear, particularly near the levee toes. Liquefaction of saturated cohesionless levee fill is a significant concern for many levees, including those in the Sacramento / San Joaquin Delta, and modifications to traditional liquefaction triggering procedures may be needed for levees on peat. More research is required to develop such modifications.

Relations for the complex shear-translation and moment-rotation responses were computed from a dynamic test of a model levee on very soft peat soil. The results indicate a significant amount of radiation damping at frequencies that are well within the bandwidth of typical earthquake ground motions and that are of interest for ground failure analysis. Whether this conclusion can be generalized to the earthquake behavior of levees resting on peat is currently unclear for a number of reasons. First, the model levee was shaken at the crest in a top-down configuration, which is different from the bottom-up propagation of seismic waves during an earthquake. Second, the model levee was smaller than typical levees, and a scale effect is possible due to the size of the levee relative to the thickness of the peat, and the higher consolidation pressures (and associated lower void ratios and higher stiffness) that would exist in the peat beneath a larger levee. Third, the model levee was a three-dimensional slice rather than a long two-dimensional earth structure that would be more consistent with a real levee. Nevertheless, the test data identified an important fundamental issue that requires further study.

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