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CENTRIFUGE EXPERIMENTS TO EVALUATE THE SEISMIC PERFORMANCE OF LEVEES ON PEATY SOILS IN THE SACRAMENTO-SAN JOAQUIN DELTA

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Abstract

The Sacramento-San Joaquin Delta lies in a seismically active region and was originally marshland, whose reclamation started 150 years ago by building levees on top of peat. Two large scale 9m radius centrifuge tests modeling the levee-peat system were conducted at the NEES facilities at UC Davis to gain insight into the complex cyclic behavior of organic soils, to shed light on the interaction between the soft peaty soil and the sandy levee material as well as on the potential of levee deformation/breaching under various ground motion intensities.

This paper focuses on the cyclic response of the system under application of a sine sweep wave. Transfer functions derived from the data and compared with 1-D theory show the existence of a rocking mode. This mechanism has not been previously described and can impose more demand on the structure and on the foundation peat due to soil-structure-interaction. A comparison of the fundamental period from recorded data to classic $4H/V_s$ estimation proves the latest to be invalid.

Introduction

Two complex large scale 9 radius centrifuge experiments (labeled RCK01 and RCK02) were performed at NEES@UCDavis equipment site to characterize the seismic response of representative levees atop peaty soils. Both tests included 2 sub-experiments: (1) the levee was first built with modeling clay placed on top of the peat and several ground motions were applied in flight to observe the seismic performance of the peat and the levee-peat system; (2) the clayey levee was then removed and substituted with a saturated sandy levee, and consequently subjected to a the target ground motion to investigate the system behavior (interaction & liquefaction). A detailed description along with test data is available in the NEES project warehouse (https://nees.org/warehouse/project/1161).

In each first sub-experiment the models were initially spun to 57 g until observing secondary compression rates, and then a series of ground motions was applied to capture the cyclic behavior under different scenarios. Important features were investigated by applying first a sine sweep wave. In this paper the response of different sections of the models to this ground motion are presented and discussed. The prototype setup before applying the sine sweep (**Figure 1**) consisted of a 5.13 m (9 cm model scale) high levee resting on top of a 8.86 m (15.55 cm) thick peat layer in Test 1 (**RCK01**) and a 6.05 m (10.65 cm) thick peat layer in Test 2 (**RCK02**).

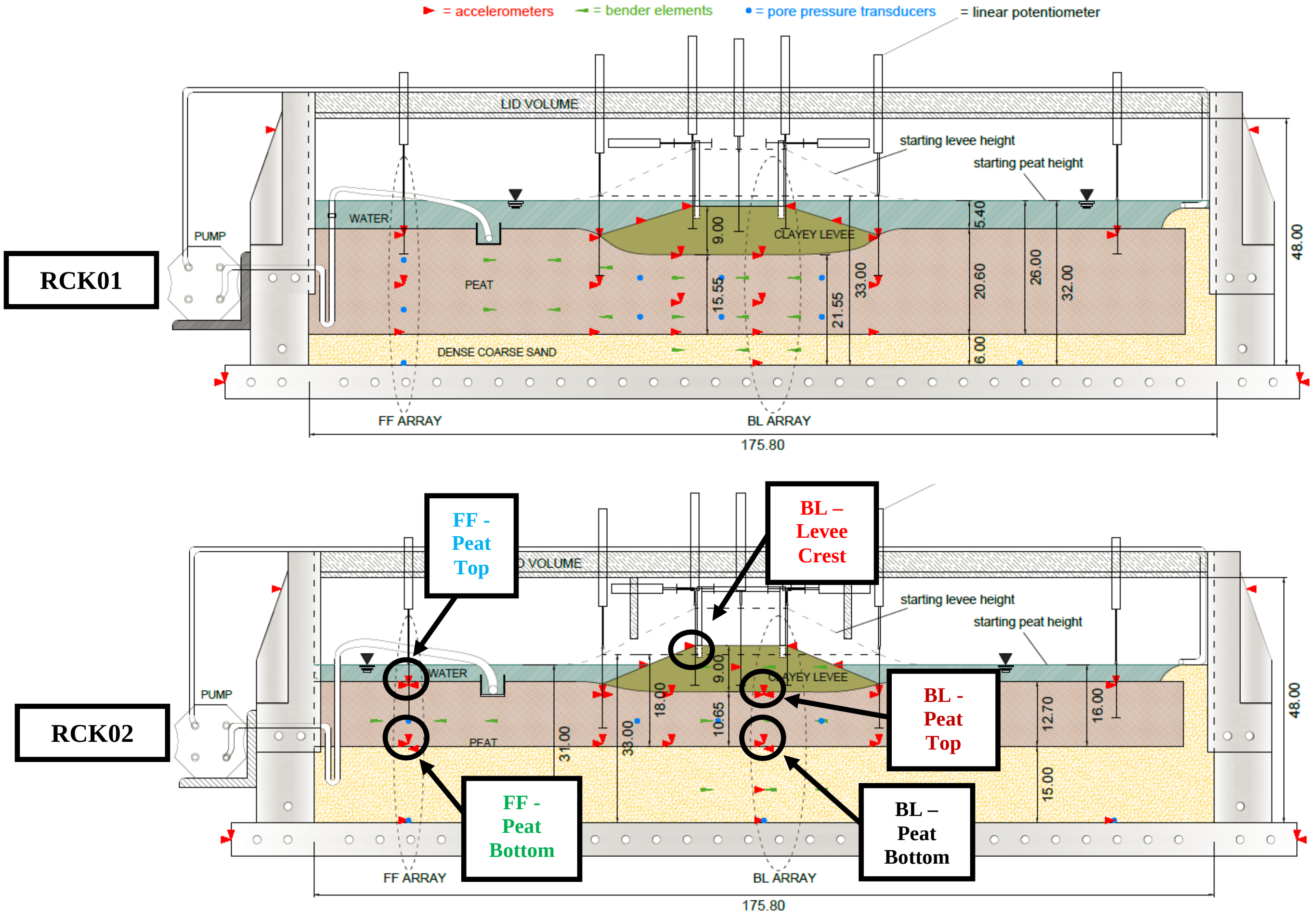

Figure 1. Setup at 57 g for First Sub-Experiment (Clayey Levee) during RCK01 and RCK02

Seismic Response of Embankments on Peaty Soils

Lying in a really seismically active region, the cyclic behavior of levee in the Delta is a serious threat to their precarious stability. Major contributions to levee deformation under cyclic loading are the potential for liquefaction of the levee fill and the deformation of the foundation peaty soil. The site response of embankments is not sufficiently defined by 1-D analyses, especially for 2-D earth structures such levees, and an underlying soft soil makes the problem even more complex.

Peat has unique characteristics such as high water content w = 500-800%, low unit weight γ = 10-12 kN/m^3, high compression indices C_c = 2-12 and low shear wave velocities V_s = 25-100 m/s Mesri (2007). Low shear strength, rate-dependent behavior and remarkable secondary compression are also notable features (Landva et LaRochelle, 1993). Due to the low shear strength, often times peat is wrongly expected to de-amplify ground shaking in seismic analysis. While this might be common for peat layer without surcharge, other situations such levees atop soft soil can greatly affect the cyclic behavior of the foundation material.

Kramer (1996) performed a series of nonlinear and equivalent linear ground response analyses and lab tests on specimens from the Mercer Slough peat, concluding that the low peat stiffness will cause ground motion long period components to be amplified, and providing the damping and modulus reduction curves as functions of effective confining pressures.

Tokimatsu and Sekiguchi (2006) discussed the responses of 3 accelerometers located on closeby arrays during the Mid Niigata earthquake (Japan, 2004) and reported that the profile with a 1.5 m of loose fill and clay atop 1.5 m of peat foresaw higher acceleration histories compared to where no peat was found.

Arulnathan (2010) used centrifuge modeling to investigate the seismic behavior of a sand-peat-sand profile and showed that the peat layer is able to greatly transmit waves during ground shaking while also sustaining large shear strains.

Kishida et al. (2009,b) developed nonlinear seismic site effect models for Sherman Island levees and plotted amplification factors (*AF)* as function of peak ground acceleration (*PGA)* for different earthquake magnitude (M_w), shear wave velocity (V_s) and normalized spectral acceleration (S_1). They observed that ground motions tend to be amplified for all period ranges when the shaking intensity is small (e.g., larger distances and smaller M_w), while when the shaking intensity is strong (e.g., small distances and larger M_w), spectral accelerations at shorter periods tend to be de-amplified but spectral accelerations at longer period such as 1.0 second continue to be amplified.

Following these studies, the potential for amplification of waves propagating through peat is substantial, and this can greatly contribute to impose higher demands on levees resting atop.

Seismic Performance of Levees on Peaty Soils in Centrifuge Experiments

The model preparation of both stages of the centrifuge experiments are discussed in detail in the reports available online at the project warehouse. A typical levee section is modeled in the selected transparent wall container and spun up to target acceleration of 57 g. After reaching primary consolidation of the peat the model is let spinning to investigate secondary compression before applying a sequence of waves. The records from slow and fast data for all the sensors (pore pressure transducers, accelerometers, linear potentiometers) as well as media files are also available at the project warehouse. **Figure 2** shows the model during construction before going on the arm for RCK01, where the clayey levee is resting atop a peat layer with dense coarse sand beneath.

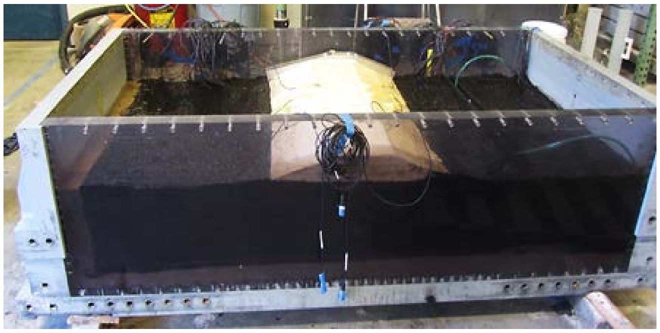

Figure 2. Model during construction for RCK01

Material characterization

Oil-based modeling clayey was initially melt and poured in a mold to obtain the model scale 9 cm height levee (= 5.13 m at prototype) with 9 cm as crest width and 2:1 slopes. This levee material was selected to be deformable but not liquefiable, therefore allowing for application of multiple ground motions.

For our centrifuge experiments bulk samples of peat were recovered from 3 m depth on Sherman Island and stored fully saturated in metal barrels at the centrifuge facility. During in-situ investigations on Sherman Island, Reinert et al. (2012) recorded CPT tip resistances below 1 MPa and an average shear wave velocity V_s of 25 m/s in the first 10 m of the peat layer. Sampling peat was gently processed by hand to remove coarse particles and long fibers that are not suitable in centrifuge modeling due to the governing scaling laws, and water was added to prevent evaporation from the fibery structure. Additional laboratory testing for this specific processed material revealed an organic content of about OC = 64 %, a specific gravity G_s = 1.85 and an initial water content of about w = 600-800 %. Reconstituted peat specimens showed a compression index C_c = 3.8 in laboratory odeometer tests in the 5-150 kPa pressure range.

The sand layer beneath the peat was slowly pluviated at high relative density to avoid its liquefaction during shaking and limit its influence on the propagating waves. At the same time the granular material better mimics the Delta in-situ condition rather than the rigid container base. Furthermore, a drainage wall on one side of the model (**Figure 2**) made with the same sandy material served as double drainage during spinning, allowing for faster consolidation time.

Soil profiles

In this paper, the cyclic behavior of two vertical arrays of RCK01 and RCK02 models during application of a sine sweep is illustrated and compared to predictions from classic wave propagation theory. The two arrays are highlighted in **Figure 1** and hereon identified as FF (Free Field) and BL (Beneath the Levee). **Figure 3** presents the FF and BL soil profiles for both RCK01 and RCK02 tests, where the unit weights were estimated as γ_{clay} = 18 kN/m^3 for the clayey levee, γ_{sand} = 19 kN/m^3 for the coarse sand, $\gamma_{peat,BL}$ = 11.14 kN/m^3 for the peat beneath the levee and $\gamma_{peat,FF}$ = 10.85 kN/m^3 in the free field for RCK01 and $\gamma_{peat,FF}$ = 10.96 kN/m^3 for RCK02.

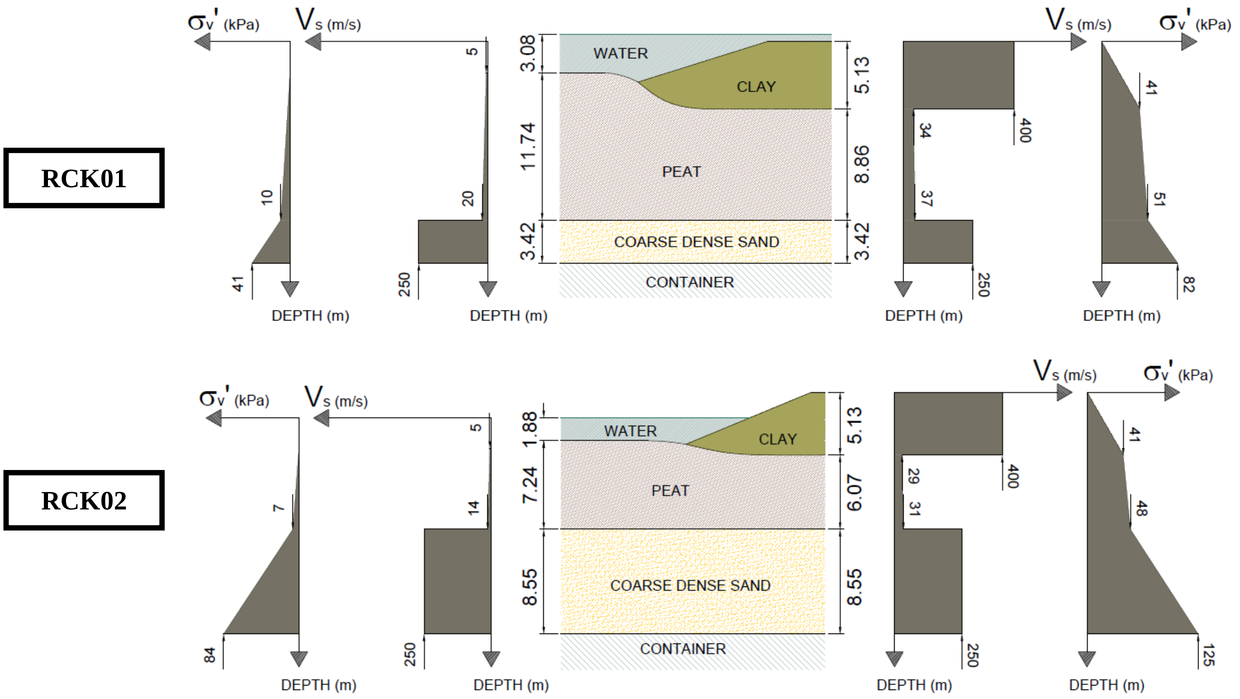

Figure 3. FF and BL soil profiles for RCK01 and RCK02

Sine sweep characterization

A common technique used in centrifuge modeling to investigate the fundamental period of a structure is to apply a sweep of sine wave with different frequencies. This allows to quickly capture which frequency contents are amplified the most and which are de-amplified. A prototype scale sine sweep from 0.12 to 5.85 Hz with 0.025 g target peak peat base acceleration (*PBA*) was modeled in displacement domain to have constant peak velocity, to which small strains can be related to. **Figure 4** shows an example of the acceleration histories recorded for RCK01 and RCK02 at peat base, free field peat top and levee crest, whose corresponding sensors' position is highlighted in **Figure 1**.

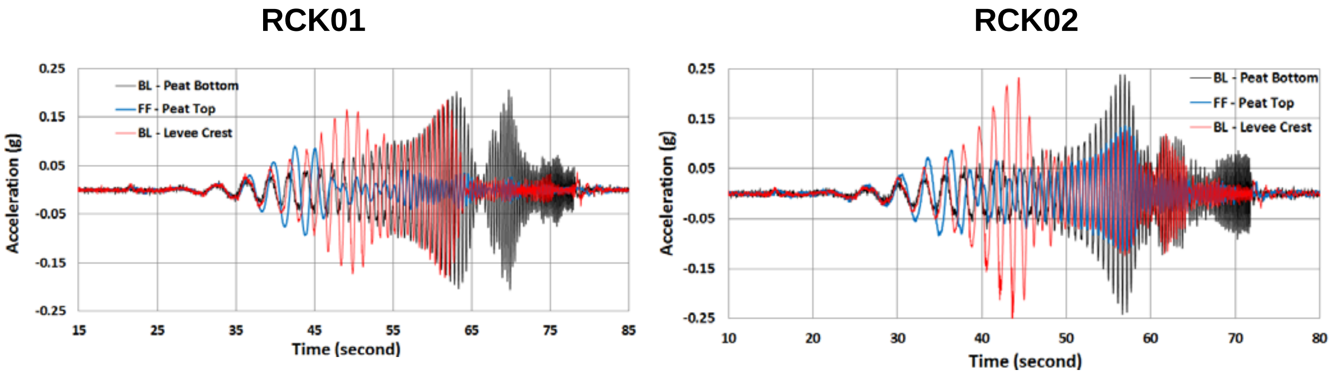

Figure 4. Accelerations at peat bottom, free field peat top and levee crest for RCK01 and RCK02 during application of the sine sweep

The blue line corresponds to the record at the top of the FF array and clearly shows how low frequencies (starting portion of the curve) are slightly amplified and shifted in time, while as we move towards higher frequencies we observe a de-amplification. On the other hand the red line (levee crest) shows a notable amplification on a broader range for low frequencies, and for a small portion of high frequencies for RCK02. **Figure 5** reports the acceleration histories of the horizontal accelerometers along the FF and BL arrays for RCK02 during the application of the sine sweep. It is clear the influence of effective stresses on the peat response and the potential for amplification of low frequencies contents over the whole levee section.

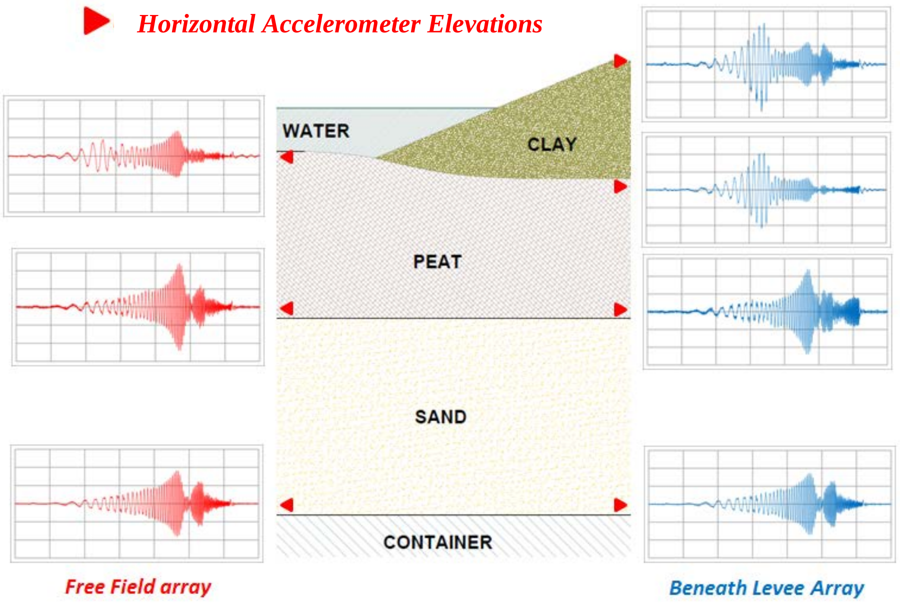

Figure 5. Records of horizontal accelerometers for RCK02

Recorded Data and 1-D Site Response Analysis

Fast data were recorded in flight at 4167 Hz during application of the sine sweep. A double integration of the accelerations permits to analyze the displacement during the ground motion. Nonzero displacements at the end of the event suggested the need to filter the acceleration to get rid of noises in the signal. A low band filter in frequency domain was applied to correct the records. The project warehouse stores both raw and corrected data. **Figure 6** shows the filtered Fourier spectra for both experiments for the BL array and the FF peat top calculated according to the following algorithm:

$$x(\omega_n)\frac{1}{\sqrt{N}}\sum_{k=1}^{N}x(t_k)e^{-1i\omega_n t_k} \qquad x(t_k)\frac{1}{\sqrt{N}}\sum_{n=1}^{N}x(\omega_k)e^{-1i\omega_n t_k}$$

where $\chi(\omega_n)$ is the Fourier spectral amplitude corresponding to the ω_n frequency calculated as a function of related time t_k and total number of elements N in the acceleration history, while $\chi(t_k)$ is its correspondent inverse.

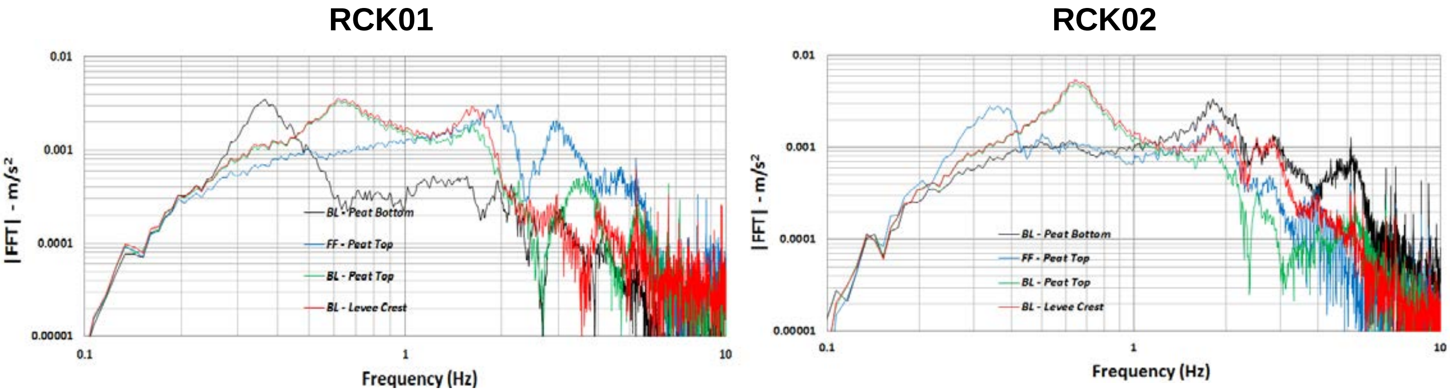

Figure 6. Filtered Fourier spectra for RCK01 and RCK02

The ratio of the spectra gives the transfer function for the sine sweep. The transfer function can also be modeled using 1-D theory, where the curve is generated as a function of soil profile properties such as shear wave velocity, unit weight, damping and layer thickness. The 1-D site response analysis was performed with the intent of comparing the ability of such method to predict the 2-D response of levees atop soft soil in centrifuge models. All the site response input soil properties were known with small uncertainty but the damping.

Kishida et al. (2009,a) presented regression models to calculate the dynamic properties of Sherman Island peat as a function of organic content *OC*, unit weight γ_c and initial effective stress σ_{v0}'. Initial predictions using the equations proposed by Kishida et al. (2009,a) to estimate damping led to really high peaks in the transfer functions, probably because of the nature of our models. In fact, unusual high damping has been observed in the past in centrifuge experiments, and the reasons are yet to be determined.

Damping was then tuned for both experiments to capture the peak value of the transfer function for the FF array, and then same properties were used to predict the transfer function from peat bottom to levee crest in the BL array. Damping of 20% was finally estimated for both RCK01 and RCK02 to sufficiently capture the peak of the recorded transfer functions in the free field arrays. Even though damping is fitted it mainly affects the height of the local peaks in the transfer function, while resonant frequencies are dictated by the rest of the parameters.

Figure 1 indicated the models were instrumented with bender elements. These piezo-sensors are capable of recording the propagation of weak mechanical waves in flight. A regression of the records from these sensors for RCK02 was used to define the relation between effective stresses and shear wave velocity (**Equation 1**):

$$V_s = V_{s1} \cdot \left(\frac{\sigma_v'}{pa} \right)^b$$

Equation 1

Where V_{s1} is 40.69 m/s, b is 0.317 and pa = 101.325 kPa is the atmospheric pressure. V_{s1} was tuned to 47 m/s for RCK01 profiles due to lack of data.

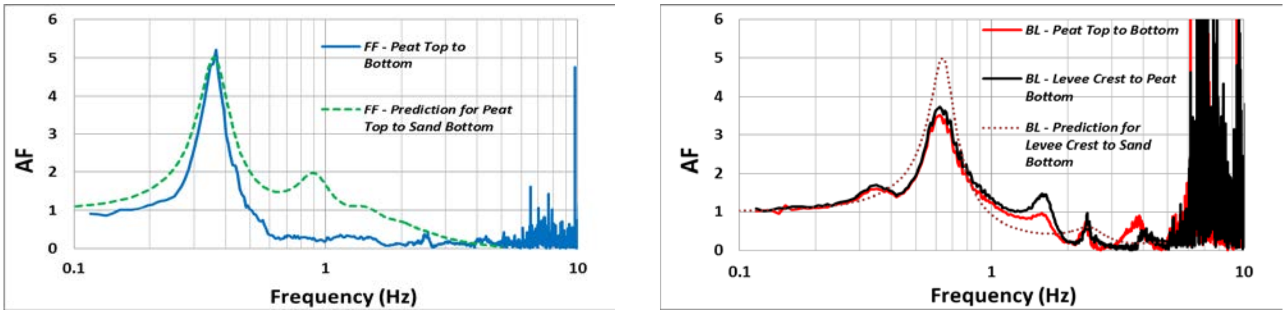

Figure 7. Amplification factors for the FF and BL profiles for RCK01

Figure 7 shows the amplification factors (top to bottom) for recorded data and 1-D site response predictions for the FF and BL profiles for RCK01. The recorded FF transfer function shows a peak at 0.36 Hz (2.77 sec) that is well captured by the 1-D analysis, with a peak of 5 as AF. On the other side, the second mode of vibration is not showed in the recorded data. For the BL array a max AF of 3.7 in the recorded levee crest to peat bottom transfer function is observed at 0.625 Hz (1.6 sec), with other 3 local peaks at 1.65 Hz, 2.4 Hz and 4 Hz. The 1-D site response analysis is again able to capture the first mode frequency but overestimates a peak of 5 as AF instead 3.7.

Moreover, a second mode is predicted for the BL array at 2.4 Hz, but not at 1.65 Hz as in the recorded data. This important difference in the transfer functions can be identified as an extra mode possibly due to rocking of the structure. AF higher than 1 for the 1.1-1.75 Hz range of frequency (black line) suggest that this rocking mode could impose higher demand on the levee itself and on the foundation peat, therefore augmenting the risk of failure. It is important to mention that real earthquakes usually have more frequency contents in that range than the applied sine sweep.

The hypothesis of a rocking monde is also suggested by comparing the rotation of the levee calculated from the records of the vertical accelerometers at the peat-levee interface beneath the embankment and the horizontal accelerometers at levee base and crest in the BL array. **Figure 8** is a plot of the Fourier spectra of the rotation of such accelerometers calculated as the FFT of the difference in the acceleration records divided by their distance, therefore resulting in radiant/s^2 units. Analogous peak in the spectra is observed at 1.65 Hz, therefore testifying the existence of a hypothetic rocking mode. **Figure 9** plots the transfer function for the horizontal pair and proves for the presence of a rocking movement of the levee during the sine sweep with a AF peaking again around 1.65 Hz.

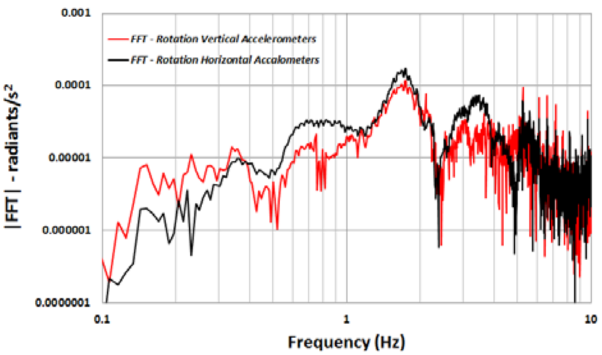

Figure 9. Fourier spectra for vertical and horizontal pairs of accelerometers for RCK01

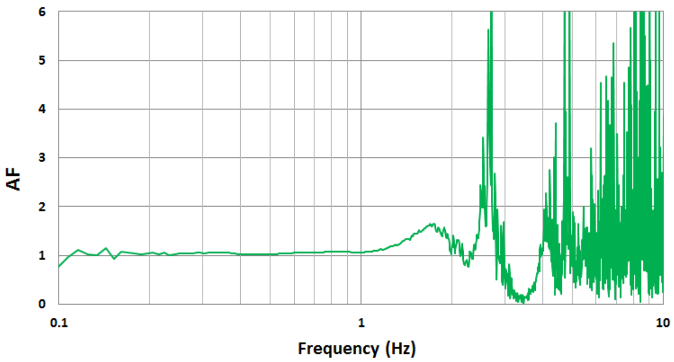

Figure 8. Transfer function for the horizontal pair of accelerometers for RCK01

Same comparison between 1-D site response analysis and recorded data was carried out for RCK02. **Figure 10** shows the transfer functions for the RCK02 arrays. The recorded FF transfer function shows a peak at 0.38 Hz (2.63 sec) that is well captured by the 1-D analysis, with a peak of 3.7 as AF. For the BL array a max AF of 5.4 in the recorded levee crest to peat bottom transfer function is observed at 0.687 Hz (1.45 sec), with two local peaks at 2.6 Hz and 3.9 Hz, which are comparable to the 3rd and 4th peaks observable in the recorded data for the same array in RCK01. In this case the 1-D theory underestimates both frequency (0.59 Hz instead 0.687 Hz) and magnitude (4.5 instead 5.4) of the first peak, but closely predicts the frequency of the second peak. This observation suggests that possibly the levees in RCK01 and RCK02 underwent different kind of movements during the application of the sine sweep, or the contributions from extra modes of vibration produced different responses. Further analysis of the data will focus on the analytical calculation of the frequency of these extra modes based on impedance functions.

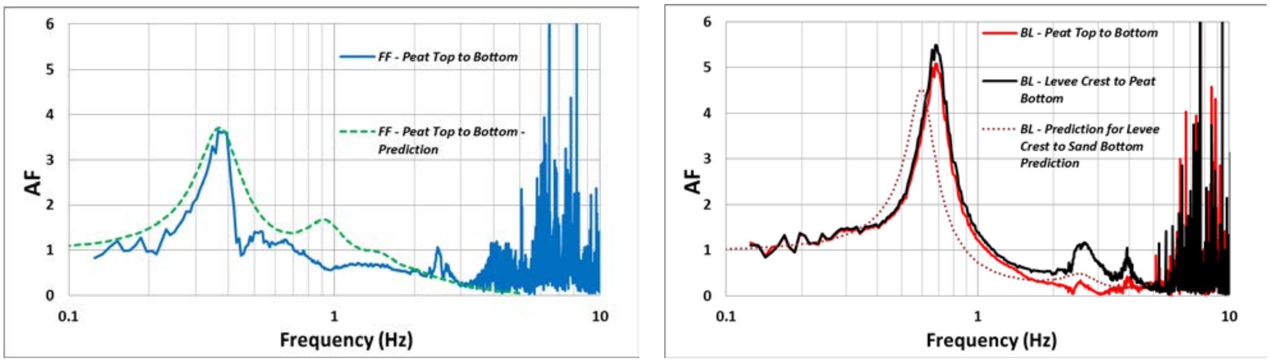

Figure 10. Amplification factors for the FF and BL profiles for RCK02

An interesting observation regards the magnitude of the first modes of vibration in the two experiments. While in RCK01 the FF array registers a peak higher than the BL, in RCK02 is the opposite. Given a damping of 20% for both tests in the 1-D analysis this can reinforce the idea that the levee in the RCK01 suffered extra modes of vibration. In fact, the recorded transfer function for the BL array in RCK01 is wider and shorter than the predicted one, meaning that radiation damping could have been substantial. In RCK02 this aspect is not observed, and the transfer function is tall and thin as the 1-D prediction, therefore damping from soil-structure-interaction could have been limited. Since impedance functions are related to shear wave velocity, a stiffer peat could also have caused less damping in RCK02. It is important to point out that even though the peat thickness of the second test was about 2/3 of the first test the cyclic response of 3-D models could greatly vary due to the complex way in which waves propagate.

Another important point could be made about the common estimation of fundamental period of a soil profile by using averaged layer thickness and shear wave velocity that is sometimes indiscriminately used for any condition. While for homogeneous soils with no overburden pressure the rough $4H/V_S$ estimation could be sufficient to give an idea of the first mode of vibration, the same shall not be applied for layered soil. A comparison of the effective difference in calculated and estimated fundamental periods for our experiments is useful to highlight the order of magnitude of the possible error. Estimations for both experiments are as follow:

RCK01: $$T_{1,FF} = \frac{4 \cdot H}{V_s} = \frac{4 \cdot 11.74}{20} = 2.35\,\text{sec} \qquad T_{1,BL} = \frac{4 \cdot H}{V_s} = \frac{4 \cdot 8.86}{37} = 0.96\,\text{sec}$$

RCK02: $$T_{1,FF} = \frac{4 \cdot H}{V_s} = \frac{4 \cdot 7.24}{14} = 2.07\,\text{sec} \qquad T_{1,BL} = \frac{4 \cdot H}{V_s} = \frac{4 \cdot 6.07}{31} = 0.78\,\text{sec}$$

where V_S and H are conveniently estimated from Figure 3. The recorded periods were 2.77 seconds and 1.6 seconds for the FF and BL profiles in the first test, and 2.63 seconds and 1.45 seconds for RCK02. Predicted fundamental periods for the FF arrays are 15-22 % off, while 40-46 % the for the BL arrays. While some error could derive from the 2-D site response instead 1-D, it is clear the limitation of this gross estimation.

Conclusions

The seismic response of embankments on soft soils is of great importance and yet little understood. A 1-D site response analysis was compared with recorded data from two large scale centrifuge experiments to investigate the cyclic behavior of a levee atop peat.

Acceleration histories and transfer functions from real data suggested the potential for amplification of a wide range of small frequency. In addition, the recorded data from the first test (RCK01) showed a local peak that is not predicted by the 1-D analysis and could be attributed to an extra rocking mode. Calculated rotations and related Fourier spectra of 2 pairs of accelerometers for RCK01 proved the rocking mode to exist. This rocking mode imposed amplification factors higher than 1 for a large portion of frequencies that are common in real earthquakes, therefore potentially augmenting the demand on the foundation soil and levee itself.

Same comparison of prediction and recorded data for the second test (RCK02) did not show same rocking behavior, but dissimilarity in the transfer function shape suggests the possibility of a different soil-structure interaction with lower damping. Future work will look more into this problem and consider the different impedance functions.

The estimation of fundamental period by the classic 4H/Vs is proved to be very rough, and shall not be used for layered soil profile. Same calculation for homogeneous layer with no surcharge pressure might be more accurate but not sufficient to capture the complex 3-D response.

Acknowledgments

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