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Settlements and excess pore pressure generation in peaty soils under embankments during cyclic loading

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ABSTRACT

A stiff levee structure made of modeling clay was placed on soft organic peat to study levee-peat interaction under different loading conditions via centrifuge testing. The model instrumentation captured the cyclic and post-cyclic response of the peat, and this paper discusses the immediate settlement, primary consolidation and secondary compression observed in the foundation soil. Excess pore pressures developed in the peat during shaking, and the secondary compression settlement rate was observed to increase due to cyclic straining. The increase of secondary compression settlement rate is consistent with laboratory test data that indicate that the secondary compression "clock" can be reset by cyclic straining.

Introduction

The global stability of embankment structures under cyclic loading may be controlled by the seismic performance of the embankment fill, or by soft foundation soils. Figure 1 illustrates failure of a levee that is impounding water, similar to levees in the Sacramento/San Joaquin Delta in California, resulting from crest settlements (e.g., induced by liquefaction or immediate seismic deformations) combined with cyclic and post-cyclic volumetric changes of the soft foundation stratum (e.g. short and long term reconsolidation). In this paper we focus on the influence of primary and secondary consolidation settlements of the foundation soil on the loss of embankment freeboard.

Over the past 20 years, the consolidation behavior of peat has been actively researched via experimental and analytical studies, (e.g. Fox and Edil 1992, Mesri et al. 1997, Mesri and Ajlouni 2007, and Kazemian et al. 2010). These studies indicate that the secondary compression behavior of peat is significant, and often dominates long-term volumetric strains. Dynamic properties of peat have also been studied (e.g., Stokoe et al. 1994, Boulanger et al. 1998, Kramer 2000, Wehling et al. 2003, and Tokimatsu and Sekiguchi 2007). Egawa et al. (2004) investigated the behavior of embankment structures on soft peat via centrifuge experiments, with a specific focus on the effects of model geometry and input motions on the accelerations and strains developed in the foundation soil, but did not describe the volume change and pore pressures generated in the peat itself. Shafiee et al. (2015) recently discovered that the secondary compression "clock" for peat may be reset by cyclic straining, potentially accelerating settlement

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of levees that survive strong shaking. The secondary compression behavior was altered when cyclic shear strains exceeded about 0.1%, while excess pore water pressures were also observed at shear strains higher than 3%.

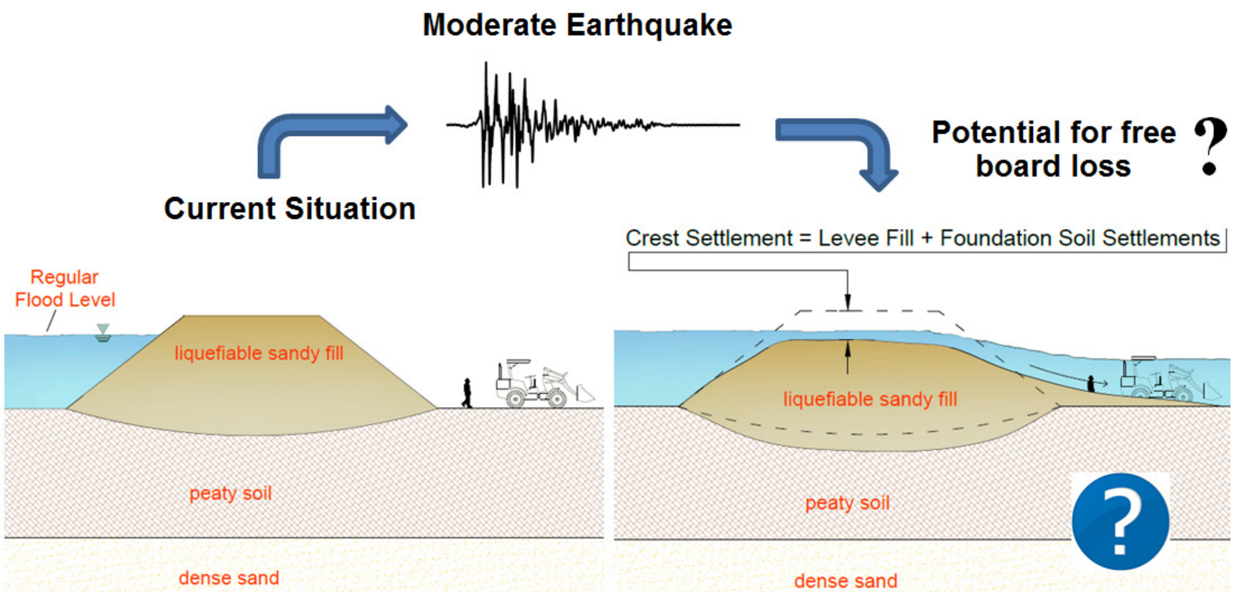

Figure 1. Crest settlement is function of seismic performance of levee and foundation soil

Centrifuge Experiments

This study aims to better understand the seismic response of levee-peat systems via two large scale centrifuge investigations (named RCK01 and RCK02) conducted at the 9m radius geotechnical centrifuge at the University of California, Davis. Each investigation consisted of two phases. In Phase 1 a non-liquefiable levee made of modeling-clay was placed atop a layer of peat (as shown in Figure 2) to study the seismic response of the organic foundation soil. Phase 2 consisted of replacing the clayey levee with a saturated sandy levee to study the liquefaction potential of the levee itself. In both phases, the models were designed and subjected to scaled target ground motions representative of the Sacramento/San Joaquin Delta. The main variation between the two investigations (RCK01 & RCK02) was the thickness of the peat layers. Experiment reports, test data and media documentation of both investigations can be downloaded from the NEES repository (https://nees.org/warehouse/project/1161).

Testing was conducted at 57g. Following spin-up, each model was allowed to consolidate for approximately one hour prior to applying the ground motions. Figure 2 shows the in-flight setup for the clay levee test (Phase 1) during RCK02 after primary consolidation. This geometry describes the model configuration before applying the ground motion series. Figure 3 captures a photograph of the experiment at this stage. Model scale geometries in Figure 2 translate to prototype dimensions of 8.55 m of dense sand overlain by 6.1 m of peat beneath the embankment overlain by a clay levee 5.1 m in height, 10.3 m in crest width and 30 m in base width with embankment slopes of 2:1 (Figure 2). The model was instrumented with accelerometers, linear potentiometers, pore pressure transducers and bender elements to capture the static (slow data, e.g. consolidation process) and dynamic (fast data, e.g. ground motion) response of the system. Dashed lines in Figure 2 indicate the initial position of the levee and peat prior to spinning. During spin up and primary consolidation at 57g, the peat in the center levee array settled approximately 7.3 cm / 4.16 m in model and prototype scale, respectively. This settlement corresponds to 40% vertical strain. The free field peat settled about 3.5 cm / 2.0 m in model / prototype scale respectively, which corresponds to 21% vertical strain.

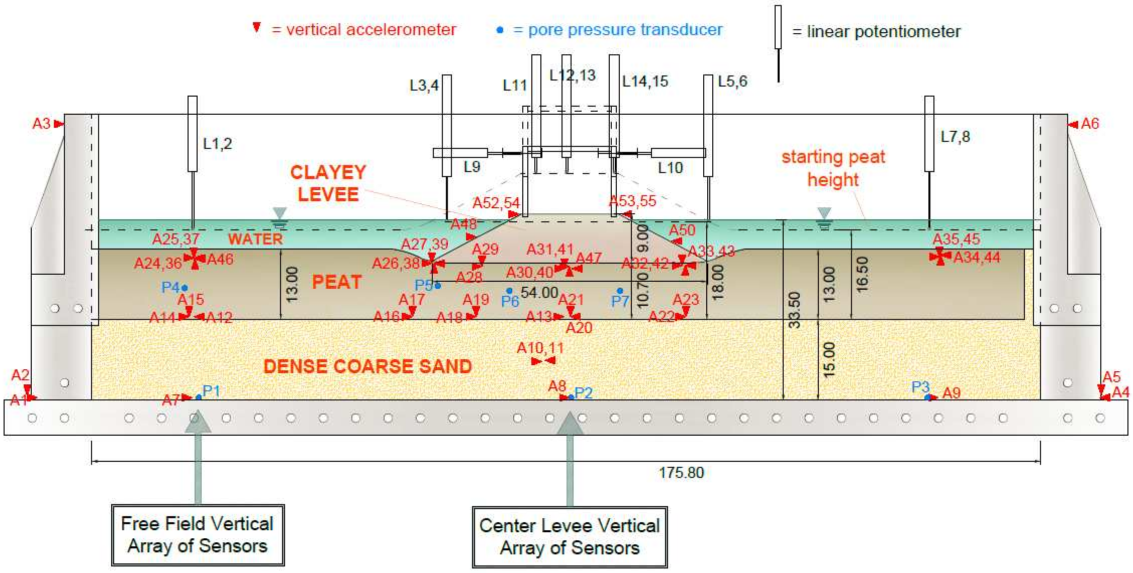

Figure 2. Experiment 14M setup at 57g after primary consolidation

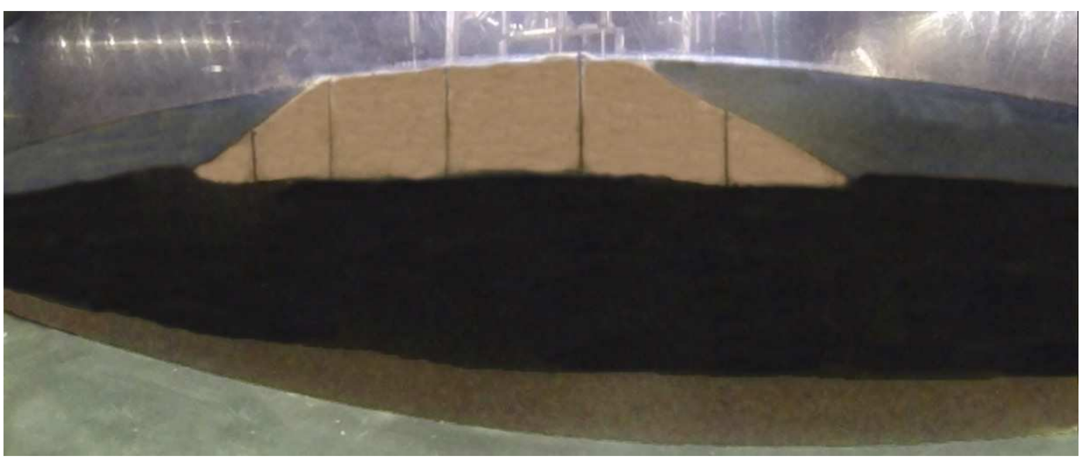

Figure 3. Side view of clay levee model at 57g after primary consolidation

Material Properties

The dense layer of coarse sand (Figure 2) was placed via dry pluviation at the bottom of the container. The material had a unit weight γ_{dense_sand} of 20.2 kN/m^3 and an approximate relative density D_R of 90%. This layer was added to simulate in-situ conditions in the Delta and to provide a drainage stratum for the peat during consolidation. The peat was excavated from a depth of 2-3 m at Sherman Island in the Delta and transported to the centrifuge facility. During storage and handling, water was added to avoid desiccation. The peat was placed into the model as a slurry, and lightly consolidated beneath a thin layer of sand. The virgin peat contained long fibers and clusters that were removed prior to placement in the centrifuge to obtain a more homogeneous material suitable for the centrifuge model. Table 1 reports the material characteristics of the processed peat determined via laboratory testing.

Table 1. Initial processed peat characteristics after laboratory test

Property	**Value**
Initial Water Content, w	670-870 %
Average Organic Content, OC	69 %
Initial Total Unit Weight, γ_t	10.28-10.41 kN/m^3
Specific Gravity of Solids, G_s	1.79
Initial Void Ratio, e_o	12-15.5
Average Compression Index in Oedometer tests, C_c	3.8

The clayey levee was constructed using oil-based modeling clay with a unit weight of γ_{clay} = 18 kN/m^3. Shear wave velocities of the different materials were measured via bender elements placed in the respective layers. Figure 4 shows estimations of prototype-scale profiles of vertical effective stress (σ'_v) and shear wave velocities (V_s) in the free-field and levee cross-sections of the model. The free-field shear wave velocities of the peat varied between 5 and 14 m/sec across the layer height. The shear wave velocity of the peat underneath the levee was measured to be 26-28 m/s.

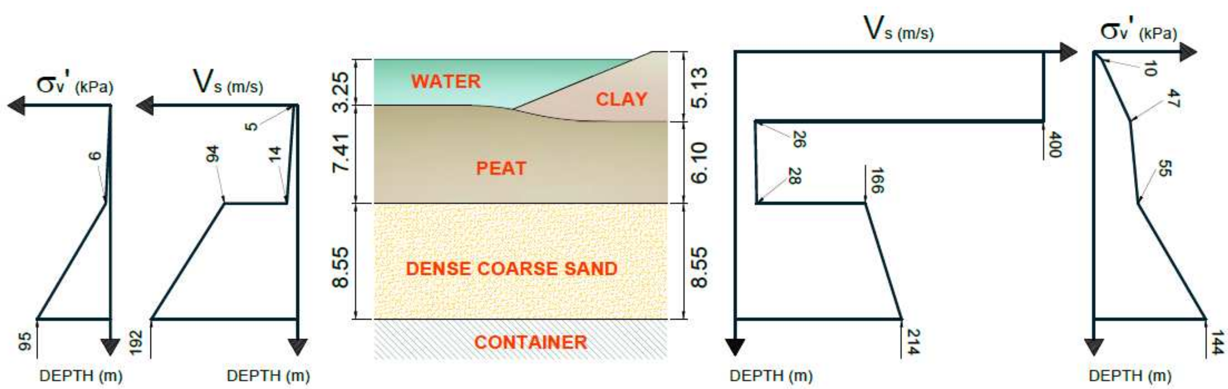

Figure 4. Free field and center arrays' soil profiles

Sample Data

Figure 5 shows the g-field, pore pressures and settlements measured during spin-up, application of ground motions and spin-down of the clay levee experiment. Data were recorded at a rate of 1 Hz. The model was spun up in step-wise increments until the target acceleration of 57g was reached. This process allowed for pore pressures to dissipate and peat bearing capacity to increase. Prior to applying the first ground motion (Strong Kobe, Trial 4) the model was subjected to a step wave (Trial 1) and a sine sweep (Trial 2) with very low amplitudes in order to check the functionality of the instrumentation and to collect useful information on the resonant frequency of the structure. In Figure 5, L11 and P6 correspond to settlements and pore pressures developed in the peat underneath the levee structure, hereafter referred to center levee array, and L2 and P4 describe the settlements and pore pressures in the free field peat.

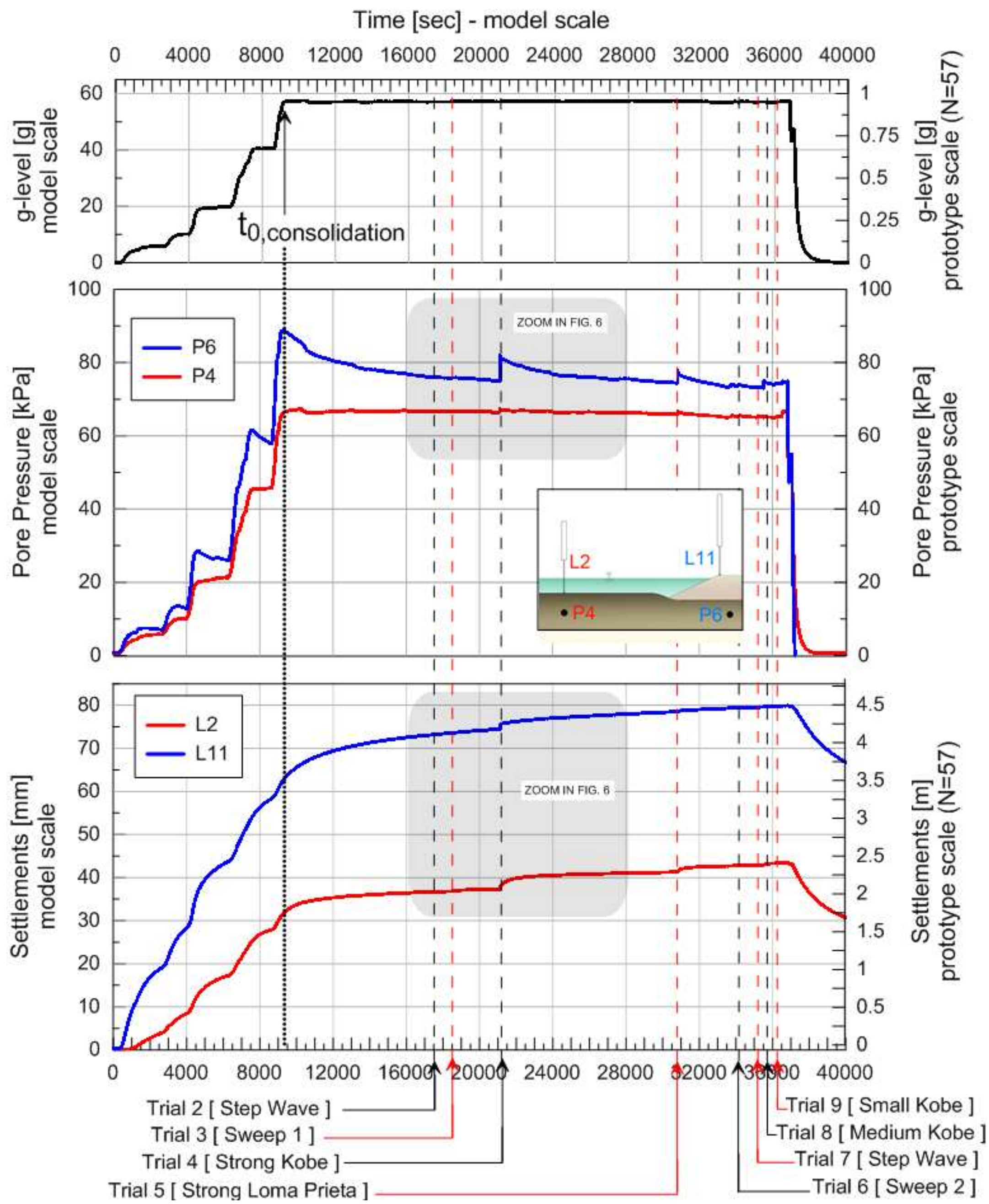

Figure 5. Acceleration (a), pore pressures (b) and vertical settlements (c) during the clay levee experiment of RCK02 (slow data)

The strong dependency of consolidation settlements on the vertical effective pressure σ'_v can be seen by comparing the linear potentiometer measurements L11 vs. L2. A settlement ratio of 2:1 between center array (65-80 mm) and free field peat (33-40 mm) was observed (Figure 5, bottom) while vertical effective stresses at mid-height peat between center array (σ'_v =51 kPa) and free field (σ'_v = 3 kPa) averaged a ratio of 17:1 (Figure 4).

Following the strong Kobe motion, the pore pressure in the free field (P4) recorded an increase of 1.1 kPa, while pore pressures underneath the levee increased by approximately 7.4 kPa. Using the estimated effective vertical stresses at peat mid-height (3 kPa for free field and 51 kPa for center levee), measurements yield excess pore pressures, r_u, of 0.36 and 0.14 for free field and center levee arrays, respectively. Figure 5 illustrates that free field pore pressures (P4) showed an almost instant dissipation after each load step, whereas pore pressures underneath the levee (P6) required much more time to reach pre-loading levels. Following earthquake application the model was allowed to enter the secondary compression stage before applying the next ground motion.

Increased Rate of Secondary Consolidation Settlements

Figure 6 presents settlement and pore pressure data measured during the application of the strong Kobe motion (Trial 4, indicated as shaded area in Figure 5). The log-scale time axis in Figure 6 is set to zero at the time the centrifuge reached 57g. Before applying the next motion (Strong Loma Prieta, Trial 5) the immediate settlements, primary consolidation and secondary compression settlements in model scale at center levee array measured approximately 1 mm, 2 mm and 1.1 mm, respectively. These data translate to prototype settlements of 5.7 cm, 11.4 cm and 6.2 cm for all three phases respectively. The total settlement underneath the center levee therefore measured 23.3 cm (prototype scale), and was recorded in just little over 9700 seconds, which translate in about 6.5 days of prototype time.

Free field model scale settlements measured 0.5 mm, 3 mm and 0.4 mm for immediate, primary and secondary compression stages, respectively. In prototype scale, their summation translates to a total settlement of 22.2 cm.

Both, free field and center levee arrays showed an increase of settlement rates during secondary compression (i.e. $\Delta\dot{u}_f > \Delta\dot{u}_0$) as indicated in Figure 6. Rates were determined by selecting settlement data corresponding to the time frame after pore pressures dissipated to pre-loading levels (i.e., primary consolidation has ceased, and secondary compression was entered).

In the center levee array the preloading secondary compression rate (in log scale) was measured $\dot{u}_{0,\,L11\,(CL)} = 7.95$ (model scale, Figure 6). The settlement rate during secondary compression after load application was $\dot{u}_{f,\,L11\,(CL)} = 9.45$. This indicates a rate increase of 18%. In the free field, the pre-load settlement rate during secondary compression was approximately $\dot{u}_{0,\,L2\,(FF)} = 2.96$. The post-load secondary compression settlement rate measured $\dot{u}_{f,\,L2\,(FF)}$ of 4.5. This represents a rate increase of 52%.

A similar tendency was observed for other ground motions. This trend suggests the potential for an additional settlement of the foundation soil when cyclically loaded, which should be taken into account during analysis as a rate adjustment / reset. Future work will investigate the correlation between secondary compression and peak ground velocity and link the magnitude of pore pressure generation and increased rate of secondary compression to the strain levels generated in the peat, as suggested by Shafiee et al. (2015).

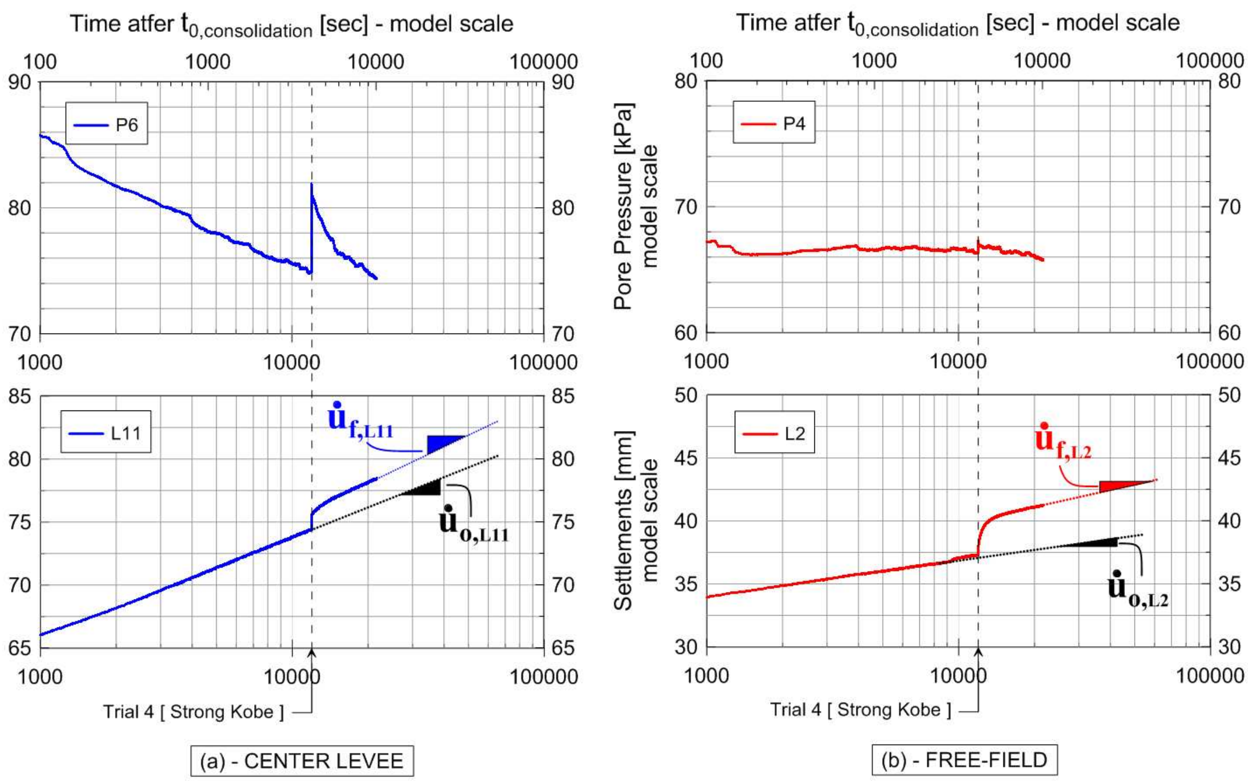

Figure 6. Illustration of secondary compression rates after cyclic loading

Summary & Conclusions

Two large scale 9m radius centrifuge tests were conducted at the NEES facility at UC Davis to gain insight into the complex SSI mechanism of levees located on soft peaty soils. This paper focused on the cyclic and post-cyclic volumetric change of the peat material and its contribution to the seismic demand on the levee structures. Rate increases in secondary compression settlements of 18% and 52% were documented in the center levee and free field arrays of the model, respectively. This suggests a strong potential hazard for accelerated long term crest settlements (i.e. reduction of freeboard) following seismic events, in particular for areas with minimal pre-earthquake secondary settlement rates. Excess pore pressures with magnitudes of 0.14 and higher were generated during cyclic loading, which enable the peat to add additional pore pressures to the sandy levee fill, therefore augmenting the risk for liquefaction failures.

Acknowledgments

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