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Remote Monitoring of a Model Levee Constructed on Soft Peaty Organic Soil

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ABSTRACT: Remote data monitoring was performed to measure settlement and pore pressure in soft peat beneath a model levee constructed in the Sacramento / San Joaquin Delta. Consolidation and secondary compression behavior was monitored following construction and dynamic testing of the model levee using piezometers embedded in the peat and an in-place horizontal inclinometer at the base of the model levee. A solar powered data acquisition system was used to gather the data, and a modem transmitted the data to a web-based interface. This system enabled us to (i) know when primary consolidation had finished prior to testing, (ii) observe the large influence of secondary compression on observed settlements, and (iii) observe a lack of any significant post-cyclic settlement. The initial change in pore pressure was predicted well using Skempton's pore pressure parameters.

INTRODUCTION

The Sacramento / San Joaquin Delta is the hub of California's distribution system, and consists of levees often resting atop very soft peaty organic soil. The levees constantly impound water and many "islands" are below sea level due to oxidation and erosion of the peat. A breach therefore causes the island to flood, and can result in hundreds of millions of dollars in damages. The Delta is sparsely populated, so the threat to life is small compared with other regions protected by levees (e.g., New Orleans), but it is nevertheless vitally important as the hub of California's water delivery system. A multitude of threats can potentially cause a breach, including piping erosion, overtopping during floods, burrowing animals, and earthquakes. The health of the levees is constantly monitored by local reclamation districts using a combination of visual inspections, inclinometers, piezometers, and satellite/aerial images. Measurements involving sensors typically require a technician to be on site to make a recording.

Seismic stability of Delta levees has recently garnered significant attention (URS 2009, Lund et al. 2007) because (i) the Delta lies in a region of moderate seismic hazard on the eastern margin of the San Andreas Fault system, and (ii) the levees are composed of engineered fill that is often liquefiable and prone to large seismic deformations. A significant concern is that an earthquake could simultaneously breach many levees, thereby flooding multiple islands and halting water delivery. A field test was recently performed to study the seismic response of the peaty organic soils that underlie many Delta levees (Reinert et al. 2012). This paper presents the remote data monitoring used to measure consolidation settlement, pore pressure dissipation, and secondary compression of the test specimen. The methods presented herein could also potentially be utilized to aid in the health monitoring of existing levees by providing spatially and temporally dense measurements without the need for an on-site technician.

TEST SPECIMEN

A model levee was constructed atop peaty organic soil on the interior of Sherman Island in the Sacramento/San Joaquin Delta. The soil profile consisted of 1.5m of unsaturated high plasticity clay and peat over 9.5m of extremely soft saturated peat over medium dense sands. Rayleigh wave velocity measured at the site was only 26m/s and water contents were as high as 700% in the saturated peat, indicating the unusually soft nature of these organic materials. Consolidation testing of the saturated peat (Shafiee et al. 2013) gives a C_c of 3.9 and a C_r of 0.4. The model levee is 1.8m (6ft) tall, 12.2m (40 ft) long along the base, 4.9m (16ft) long along the crest with 2:1 sideslopes, and 3.7m (12 ft) wide (out of plane). A schematic of the model levee and instrumentation plan utilized to monitor consolidation and secondary compression is shown in Fig. 1. Sandy clay fill, sourced from a local borrow pit on Sherman Island, was compacted in six lifts, and reinforced with a combination of Tencate 2XT biaxial geogrid and Mirafi 500x woven geofabric. The clay was compacted to a dry density of 17.3 kN/m^3 (110 pcf) at 11% water content. The geogrids were wrapped in the out-of-plane direction in order to form two vertical faces on the edge of the embankment. A sturdy timber frame was embedded into the upper 3 lifts of the embankment to support an eccentric mass shaker (MK15). A photo of the constructed embankment, with the shaker attached is shown in Fig. 2.

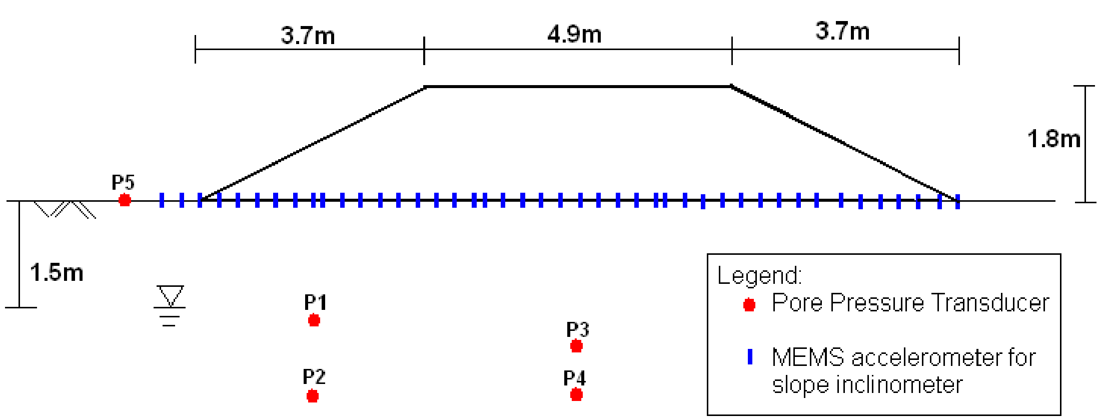

Fig. 1. Schematic of test levee with sensors used in long-term remote measurements.

Fig. 2. Photo of model levee.

SENSORS

An in-place inclinometer was used to monitor settlement of the embankment, and piezometers were used to monitor pore water pressure. The in-place inclinometer, manufactured by Geodaq, Inc., consists of five model INC500 modules connected end-to-end forming a continuous displacement measurement system with a total length of 13m (42.5 ft). The in-place inclinometer does not require passage of a traditional inclinometer sensor through the casing, as do many other inclinometers. Rather, each INC500 module includes 8 Micro-Electro-Mechanical Systems (MEMS) accelerometer sensors spaced 0.30m (1 ft) apart for a total of 40 bi-axial MEMS distributed over the full length of the model levee. MEMS sensor readings were recorded at 10 minute time intervals over a period of 325 days, and displacement profiles were calculated by spatially integrating the measured rotations along the inclinometer axis.

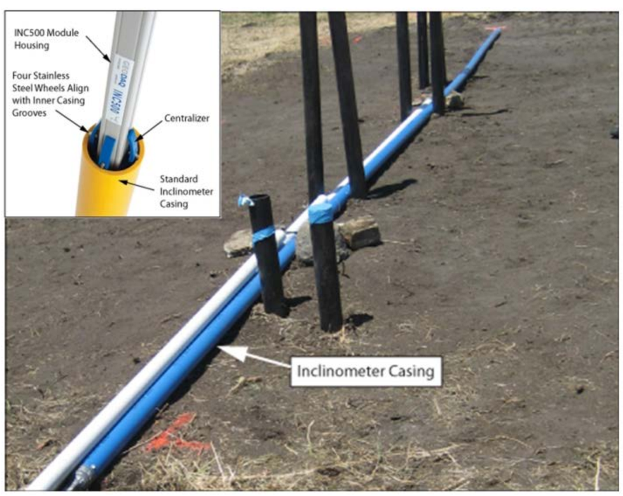

Fig. 3. Inclinometer casing on ground surface prior to levee construction, and INC500 instrumentation detail.

The INC500 inclinometer sensor network was installed inside a standard 7mm (2.75 inch) diameter inclinometer casing placed horizontally on the ground surface prior to construction of the test levee embankment as shown in Figure 3. A total of 25 centralizers were attached to the INC500 modules with a center-to-center spacing of about 0.5m (20 inches). Each centralizer is specifically designed with four wheel assemblies to track the inside grooves of the inclinometer casing and this feature ensures accurate sensor alignment over the full length of the casing. The centralizers also provide a simple way to remove the INC500 modules from the casing for comparison to manual probe surveys or for re-use on other in-place inclinometer monitoring projects.

Pore water pressure beneath the levee embankment was monitored at four positions using KPSI 330 piezometers manufactured by Measurement Specialties. The piezometers were wrapped with a cloth to filter the soil solids, and installed beneath the levee at depths of 1.95m (P1), 2.33m (P3), and 3.17m (P2 and P4) to monitor changes in pore pressure during construction of the levee embankment and during long-term consolidation of the peat (Fig. 1). The peat was so soft that the piezometers were simply pushed by hand to the desired depth using a mandrel. The KPSI 330 transducer is an electrical resistance type sensor that converts water pressure acting on a diaphragm to an analog voltage output. The back side of the diaphragm was sealed rather than vented to the atmosphere, rendering the piezometers sensitive to changes in atmospheric pressure. Since pore pressure relative to atmospheric pressure was desired, a piezometer was also placed above the ground surface to measure atmospheric pressure. Each piezometer was connected to a GST module that operates on the same digital network as the INC500 modules. Each GST network module includes a microprocessor, signal conditioning circuitry, a 16-bit analog-to-digital conversion circuit, and Controller Area Network (CAN) communication controller.

REMOTE DATA ACQUISITION SYSTEM

Sensor readings were digitized at each network node (five INC500 modules and two GST modules) at 10 minute sampling intervals and results were transmitted to a controller module (GCM) using a two wire Controller Area Network (CAN) communication system. The GCM module collects readings from the entire network and transmits the data to a web server computer via a wireless Internet modem. A monitoring station at the ground surface includes one controller module (GCM), one Internet modem, one battery and a solar panel to charge the battery. The remote monitoring station used for this project is shown in Figure 4. A steel frame with locking lid was mounted to the ground with anchors to provide protection from vandalism and cattle. All piezometer and inclinometer readings were transmitted through the plastic field enclosures, so no external components were visible and all the monitoring instrumentation maintained a low profile.

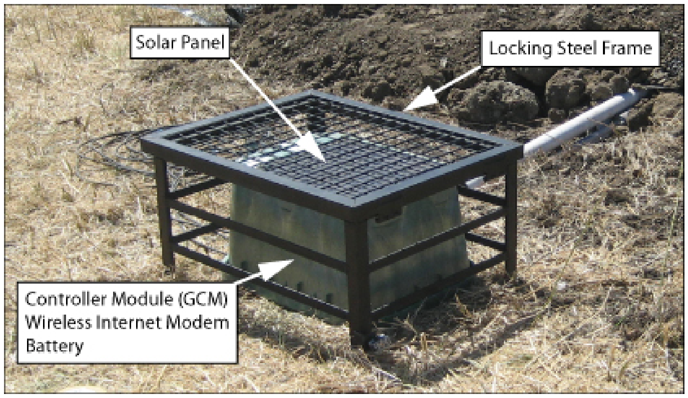

Fig. 4. Remote monitoring station.

TEST DATA

The test data is presented over two different time intervals of engineering interest. First the data is presented for 40 days beginning with construction of the embankment and ending a few days after dynamic testing. The reasons for presenting data for this time interval are to document the consolidation behavior of the peat following construction of the embankment, and to document any post-cyclic settlement following dynamic testing. The second time interval covers nearly a year, beginning with embankment construction. The purpose of presenting data from this time interval is to show changes in the groundwater level associated with pumping operations on Sherman Island, and the influence of these fluctuations on the embankment settlement.

Figure 5 shows settlement beneath the crest of the levee and pore pressure from the four subsurface piezometers for 40 days following construction of the embankment. Atmospheric pressure was subtracted from the four subsurface piezometer records. The recordings begin on Thursday, July 28th, 2011, when the first of six lifts was constructed. The following day, two additional lifts were constructed. Finally, following a weekend break, the final three lifts were constructed on Monday, August 1st. Piezometers P2 and P4 exhibit pronounced increases each time a lift of fill is placed, and a subsequent slow decrease due to consolidation. Piezometers P1 and P3 exhibit much smaller increases, likely because their close proximity to the ground water table places them near a drainage boundary, where pore pressure decreases rapidly. The piezometers indicate that the peat consolidates rather quickly because excess pore pressures generated by constructing lifts 2 and 3 on July 29th had essentially dissipated prior to construction of lifts 4, 5 and 6 on August 1st. Following construction of lifts 4, 5 and 6, pore pressures continue to decrease slowly throughout the 40 day period, returning to pre-construction levels after 10 days, and subsequently continuing to decrease. Pumping operations on Sherman Island drew down the groundwater table, which explains why pore pressures reduced below pre-construction levels.

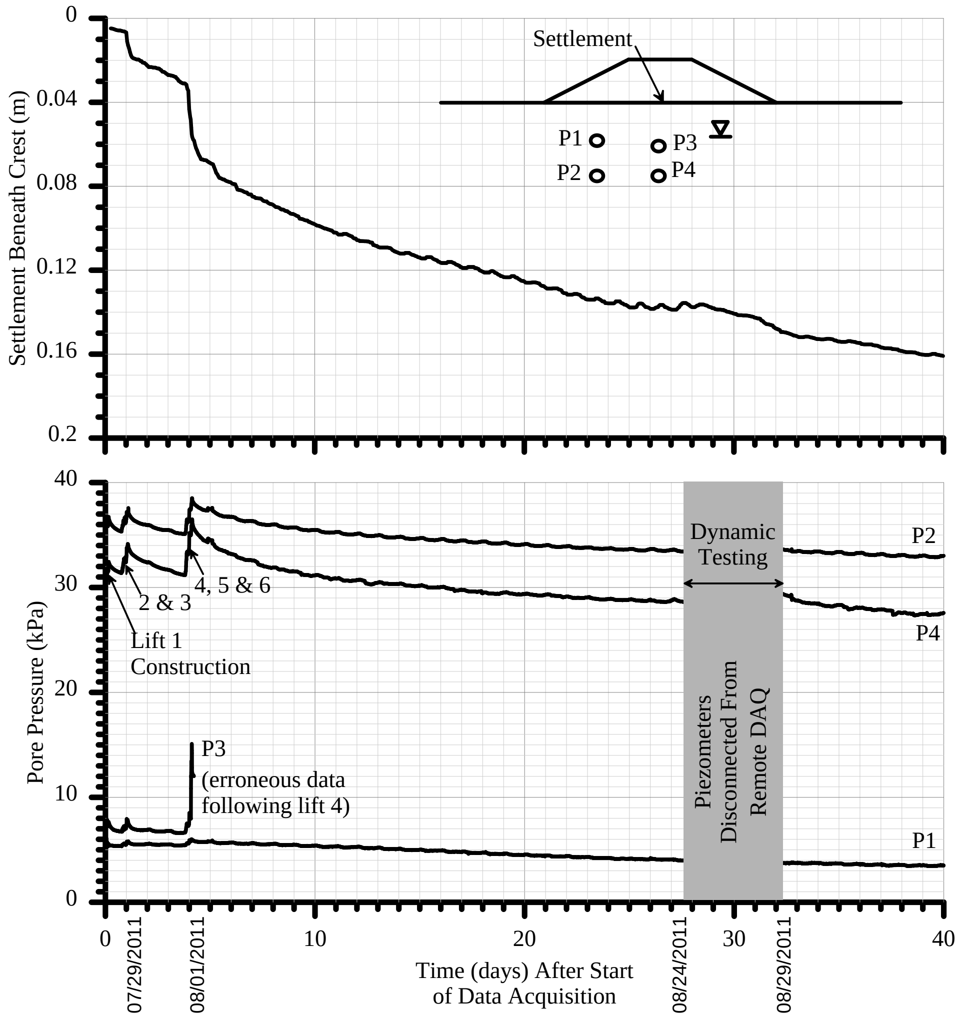

Fig. 5. Settlement beneath levee crest and pore pressure at various positions beneath the embankment versus time for 40 days following embankment construction, including the period following dynamic testing.

The settlement data exhibit sharp increases during placement of the fill due to shear-induced immediate settlement of the embankment. The immediate settlement obtained by summing the abrupt increases in settlement was approximately 0.06m. The settlement also exhibits a slower increase over time due to the combined effects of primary consolidation and secondary compression. High secondary compression is inferred from the rapid settlement rate following dissipation of pore pressures to pre-construction levels after 10 days. High secondary compression is a common feature of peat soil that is well documented in the literature (e.g., Mesri and Ajlouni 2007), and is usually attributed to high void ratio of peat, high ratios of the index of secondary compression to the compression index (C_α/C_c), and high initial permeability of the peat (Mesri et al. 1997) . In laboratory oedometer tests performed on piston samples retrieved from the site (Shafiee et al., 2013), distinguishing primary consolidation from secondary compression using Casagrande's (1938) procedure was difficult due to the high c_α.

The piezometers were disconnected from the remote data acquisition system on August 24th, connected to a different data acquisition system utilized during dynamic testing of the embankment, and subsequently reconnected after dynamic testing on August 29th. The inclinometer remained connected during this time. Dynamic testing of the embankment was intended to induce shear strain into the peat over a range of shaking intensities to observe the response. No increase in settlement was observed following dynamic testing. This may be attributed to the stiffer, unsaturated peat in the upper 2m, which thwarted transmission of shear strain into the soft underlying saturated peat.

An interesting observation is that the change in pore pressure induced by the surface loading is less than the change in vertical total stress at the piezometer position. For example, lifts 4, 5 and 6 combined to induce a vertical stress change of approximately 16 kPa at the surface. Elastic solutions predict that the vertical stress change at a depth of 3.0m (i.e., the depth of P2 and P4) is 8.8 kPa at the position of P4 and 6.7 kPa at the position of P2. The changes in pore pressure, on the other hand, were only 5.5 kPa and 3.7 kPa for P4 and P2, respectively. The difference between the change in vertical stress and the change in pore pressure is likely caused by (i) three-dimensional loading conditions (i.e., Skempton and Bjerrum 1957), (ii) dissipation of excess pore pressure during the short time during which fill was added to the model levee, and (iii) the lateral distribution of stress through the stiffer unsaturated peat layer above the water table.

Pore pressure at the depth of P2 and P4 was more than 30 kPa at the time of dynamic testing, which is quite a bit higher than would occur for hydrostatic conditions. The transducers were approximately 1.6m below the water table, hence hydrostatic water pressures would be expected to be approximately 16 kPa. This condition can be explained by the site geology. The peat is underlain by a permeable sand layer that is continuous and connected to the San Joaquin River. Therefore, the pore pressure at the bottom of the peat layer is controlled by the river elevation rather than the depth below the water surface in the peat. The continuous pumping of water from Sherman Island maintains the water elevation within the peat, inducing an upward hydraulic gradient (artesian condition) and larger-than-hydrostatic pore pressures. Artesian conditions were subsequently confirmed by CPTu tests, which indicate that the pore pressure in the sand underlying the peat is approximately 50 kPa higher than hydrostatic.

Figure 6 shows data recorded over a span of 325 days. The pore pressure records demonstrate a sudden increase in pressure approximately 70 days after construction of the embankment. This sudden increase is due to pumping operations on Sherman Island, and fluctuations in water level are common, with the lowest levels near the end of the summer and highest levels in the winter. The peak pore pressure for P1 reached about 17kPa, indicating the water table was at or near the surface during much of the wet season. Water pressures then slowly began to decrease after about 260 days. Settlement continued to accumulate during this time, reaching about 0.27m at 325 days.

Settlement profiles at various times are shown in Fig. 7. The settlement is largest beneath the crest of the embankment and increases with time, as anticipated. These profiles are computed by integrating the measured rotation data along the inclinometer axis, resulting in a measurement of relative displacement with respect to one end of the inclinometer casing. Rigid body translation of the inclinometer casing is not measured by the MEMS sensors, but could conceivably be measured by an independent sensor. An attempt to measure the settlement of the ends of the inclinometer casing using string potentiometers suspended from taut cable lines failed because the string potentiometers became entangled in vegetation. The assumption of zero settlement at horizontal position = 0m as shown on Fig. 7 is considered to be reasonable based on field observations.

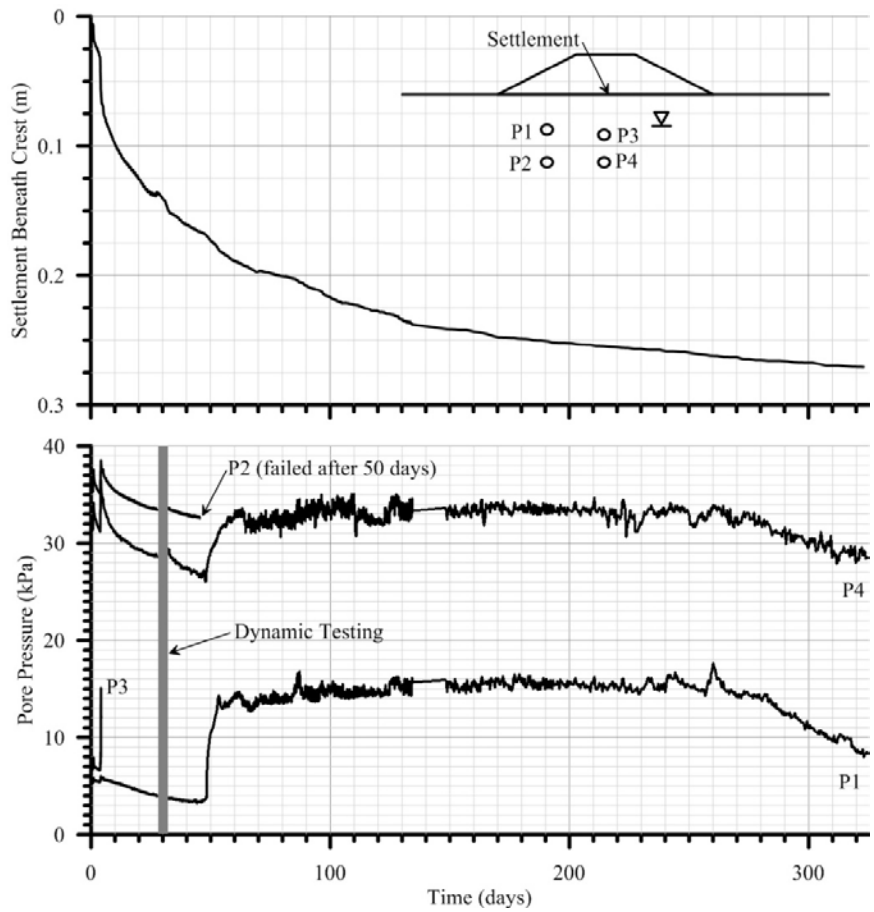

Fig. 6. Settlement beneath levee crest and pore pressure at various positions beneath the embankment versus time for 325 days.

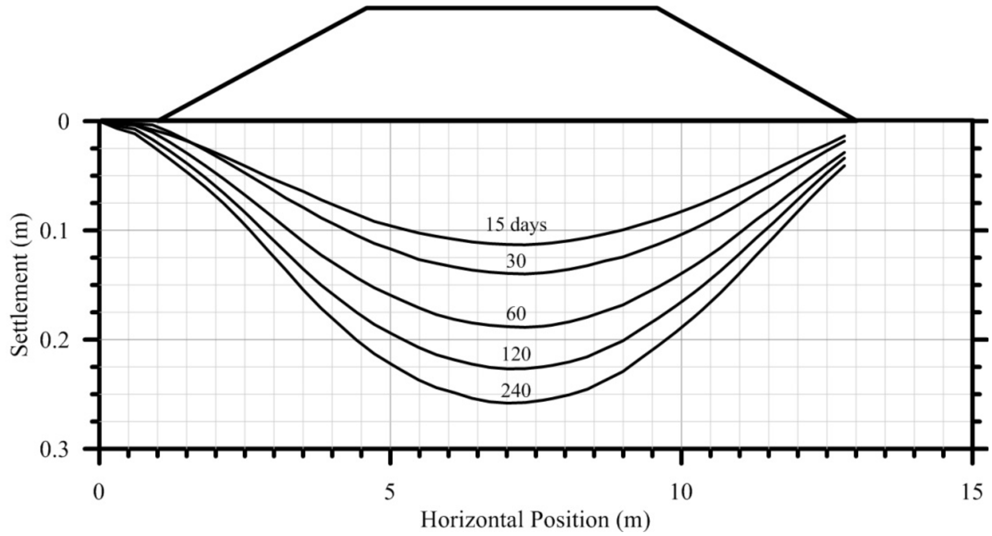

Fig. 7. Settlement profiles at various times following construction of the model levee.

CONCLUSIONS

A remote data acquisition system was utilized to monitor settlement and pore pressure following construction of a model levee on very soft and compressible peaty organic soil. A spatially dense in-place inclinometer and piezometers were sampled at an interval of 10 minutes, and data were communicated to a website via a modem, thereby eliminating the need for a technician to gather these important measurements. The measurements show that (i) the peaty organic soil consolidated rather quickly following construction of the embankment and excess pore pressures dissipated within approximately 10 days after construction, (ii) the embankment continued settling after excess pore pressures had dissipated, indicating significant secondary compression, which is common for peat soil, and (iii) ground water levels rose rapidly approximately 70 days after construction of the embankment due to ground water pumping operations.

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