Characterizing the Seismic Threat to California’s Water Supply

By Scott J. Brandenberg, Ph.D., A.M.ASCE, Jonathan P. Stewart, Ph.D., P.E., F.ASCE,
and Robb E.S. Moss, Ph.D., P.E., M.ASCE

including floods, climate change, burrowing animals, and invasive species. However, the earthquake hazard is particularly onerous due to the potential for widespread simultaneous breaches of many levees and inundation of the land circumscribed by the levees (i.e., "islands"), much of which is below sea level. Many of the levees are founded on peaty organic soil whose cyclic properties are poorly understood, which complicates engineering evaluation of seismic stability.

The Delta’s History

The Sacramento-San Joaquin Delta is a 700,000-acre estuary at the confluence of the Sacramento and San Joaquin rivers, which drain California’s central valley west into the San Francisco Bay. Prior to the mid-19th century, the Delta served as a rich hunting, fishing, and foraging region for Native Americans. Natural levees were formed by repeated historical flooding, but nearly 60 percent of the Delta was submerged daily by tides, and large areas were often inundated by seasonal river flooding.

The widespread failure of the New Orleans levee system caused by Hurricanes Katrina and Rita in 2005 was a warning for California, where the Sacramento-San Joaquin Delta levees are part of the system that delivers fresh water to over 22 million residents and protects farmland and wildlife habitat. The Delta is exposed to a multitude of hazards,

The numerous plant species that thrived in the Delta, combined with sediments delivered by historical flooding, formed thick layers of peaty organic soil that is rich in nutrients and extremely compressible. These rich peaty soils led settlers to begin farming the natural levees in the mid-19th century. Limited availability of natural highlands in the Delta resulted in efforts to reclaim the low-lying areas by placing fill atop the natural levees. A "levee war" ensued in which farmers raced to make their levees higher than their neighbors. Many levees are therefore not engineered structures. Rather, they generally consist of uncompacted to poorly compacted sands, clays, and organics often founded on peaty organic soil.

To enhance reclamation efforts, the State of California began selling Delta lands at a low cost in 1858, and local reclamation districts were formed from collections of smaller parcel owners. Large islands were enclosed by levees as technology permitted more rapid construction by mechanized dredging, fill placement, and pumping of
low-lying areas (Figure 1). Between 1860 and 1930, a total of 441,000 acres were reclaimed.

Following reclamation, focus shifted to water storage and delivery to more arid regions of the state. The federal government funded the Central Valley Project in 1933 to deliver water to the San Joaquin Valley, and beginning in 1960 the State of California enacted the State Water Project to deliver water to Southern California.

Subsidence and Consequences of Flooding

Historical flooding that had delivered sediments to the Delta before reclamation has been largely controlled in the past century as the Delta was maintained as a fresh water conveyance system. Furthermore, drying and tilling of farmland has caused oxidation and wind erosion of the peaty organic soils in the interior of the islands, and subsidence of some islands has exceeded rates of 10 cm/year. Many islands now lie as much as 3 to 5 m below sea level, and often provide only 1 m of levee freeboard at high tide. A levee breach therefore draws a significant volume of water into the island and large-scale inundation during periods of low fresh water outflow can locally reverse the flow direction, drawing saline water east from the San Francisco Bay into the Delta.

This is a potentially catastrophic scenario, as water intakes for central and southern California could be compromised, removing the sole water source for many communities and inundating farmland and wildlife habitat. Such large-scale inundation is unlikely in the event of an individual levee breach caused by burrowing animals and other local hazards because the existing emergency response system can respond to a single breach within a matter of hours and effect repair within a matter of weeks.

Seismic Hazard

The seismic hazard is exceptional because of the potential for multiple simultaneous breaches inundating many islands within the Delta. Peak horizontal acceleration of 0.35g has a return period of 500 years in the western Delta and according to the California Bay Delta Authority, this shaking level would be expected to cause 10-70 failures of the existing levees. These failures would flood multiple islands, draw in saline water from San Francisco Bay, and compromise water quality at pumping station intakes. Such widespread system failure has been forecast to interrupt fresh water deliveries from the Delta for 20 to 30 months.

The State of California recently sponsored the Delta Risk Management Strategy (DRMS) to quantify seismic risk and flood risk in the Delta. The seismic evaluation separated levee sites as being potentially liquefiable or non-liquefiable, with peats being classified as non-liquefiable soils. Liquefaction of coarse-grained materials within and beneath the levees was recognized as a significant problem based on observed levee failures from many regions around the world, including Japan, China, Taiwan, and California.

Hazard to levees underlain by or comprised of nonliquefiable soils were evaluated in the DRMS study using Newmark sliding block analysis. The Newmark approach is well-established for problems involving sliding or shear deformations, but its applicability to problems involving levees on peaty organic soils is unknown. Peat is more pervasive than liquefiable sand in the Delta, but much less is known about its seismic behavior.

Observations from the Delta levees themselves cannot be used because they have not been subjected to strong ground motion in their current configuration. Levees on peat soils have been shaken elsewhere, often with poor performance, but the lessons from these case studies are often difficult to learn.

The mechanisms by which levees founded on soft peaty soils might fail under seismic conditions are not adequately understood. Several possible failure mechanisms for non-liquefiable soils that could cause a critical loss of freeboard and overtopping are shown in Figure 2. One mechanism is levee settlement due to post-cyclic volumetric strain in the underlying peaty soils. This mechanism is not captured by

Figure 2: Potential failure mechanisms of levees on peaty organic soil.
Newmark analysis, but cyclic triaxial tests have shown that peat specimens can exhibit post-cyclic volumetric strain that would cause settlement following an earthquake.

Additional levee failure mechanisms include sliding on top of cyclically-weakened peat due to hydrostatic pressures and seismic loads, or bearing failures resulting from distributed shear deformations in the peat. On a conceptual level, such mechanisms might be amenable to Newmark analysis, although the analysis would be complicated by the very low shear modulus exhibited by peat soils. Better information is needed to develop reliable evaluation procedures for seismic deformations of levees on peat.

**Full-Scale Dynamic Testing**

Peaty organic soils are very difficult to sample and test in a laboratory, and the constitutive behavior can be highly anisotropic and difficult to model accurately, which complicates the use of model scale tests or numerical models to assess critical deformation mechanisms. Thus, full-scale testing of a test levee has begun to investigate the *in situ* deformation potential of the peaty organic foundation soils under realistic shaking. Ideally, an existing levee section would be tested to best replicate field conditions, but nearly all levees in the Delta currently impound water and the consequences of damaging a levee are too high. Hence a small test levee will be constructed on the interior of an island, far away from existing levees, and testing will proceed after the highly permeable peaty soils have consolidated.

This NSF-sponsored research will use the large-scale eccentric mass shakers to cyclically load the test levee and the underlying peats into the nonlinear range, with accelerations consistent with anticipated earthquake ground motions. The eccentric mass shaker will be bolted to a concrete foundation on the crest of the test levee.

The test conditions and instrumentation have been designed to measure the deformation mechanisms that result in a critical loss of freeboard leading to a breach. Data of this sort is essential for the development of more rational (and meaningful) analysis tools for assessing the seismic vulnerability of levees. Instrumentation (Figure 3) will monitor accelerations on the ground surface and within the levee and foundation, as well as pore pressures in the foundation soils during shaking. Slope inclinometers and settlement markers will be used to evaluate deformation mechanisms caused by shaking.

The field testing is being supplemented by an extensive laboratory testing program to investigate key material response characteristics such as cyclic pore pressure generation and its effects on shear strength and post-cyclic reconsolidation. Cyclic laboratory tests of peat samples recovered from the field test site will be performed to help evaluate whether the deformation processes observed in the field are predictable using laboratory-derived soil properties coupled with appropriate deformation analysis procedures.

**Expected Outcomes**

The research project will provide an important data point for calibrating engineering evaluation procedures for predicting seismic deformation mechanisms of levees on organic soils. Better understanding of cyclic strength loss and post-cyclic volumetric strain in peats will permit rational evaluation of levee deformation using procedures analogous to those already established for sands and...
clays. A single test cannot fully represent the possible combinations of levee configurations, foundation soil conditions, and shaking demands, but hopefully this pilot test will open the door to more testing to continue filling gaps in our knowledge. The project has potential to significantly impact and improve the ongoing concerted efforts to characterize Delta risk in California, and advise decisions regarding Delta land use and water delivery policy.

Scott J. Brandenberg, Ph.D., A.M.ASCE, is an assistant professor in the Department of Civil and Environmental Engineering at UCLA. Scott's primary research interests are in geotechnical earthquake engineering with a focus on the effects of lateral spreading against pile foundations, centrifuge modeling, and geophysical imaging of embedded objects. He can be reached at sjbrandenberg@ucla.edu

Jonathan P. Stewart, Ph.D., P.E., F.ASCE, is a professor in the Department of Civil and Environmental Engineering at UCLA. Jon's primary research interests are in geotechnical earthquake engineering, with emphases on seismic soil-structure interaction, probabilistic characterization of site effects on earthquake ground motions, seismic compression of unsaturated soils, and ground failure in sands as well as marginal plasticity soils. He can be reached at jstewart@seas.ucla.edu

Robb E.S. Moss, Ph.D., P.E., M.ASCE, is an assistant professor in the Department of Civil and Environmental Engineering at Cal Poly, San Luis Obispo. Robb’s research interests include probabilistic assessment of liquefaction triggering and tsunamigenic fault rupture, effects of aging on liquefaction resistance, acquisition of liquefaction field case histories, pile design for dynamic lateral loading, and environmental impact of chemical grout. He can be reached at rmoss@calpoly.edu

Geo-Strata is interested in hearing from you. Please send your comments on this article to geo-strata@asce.org.

"CPT: The Tool to Manage Your Risk"

A. P. Van den Berg® Inc.

Cone Penetration Test (CPT) Equipment

Skid-mounted equipment with or without cabin available for USA market

GEOTECHNICAL- ENVIRONMENTAL- SEISMIC
Hydraulic Penetrometers - Electrical & Mechanical Cones
Specialized systems for data acquisition, sampling and drilling


A. P. Van den Berg, Inc.
P.O. Box 654
Milford PA 18337
USA
Tel: 570-296-8224
Fax: 570-296-4886
E-mail: apvdberg@ptd.net

A. P. Van den Berg, B.V.
P.O. Box 68
8440 AB Heerenveen
The Netherlands
Tel: +31 513 63 1355
Fax: +31 513 63 1212
E-mail: info@apvdberg.nl

Web: www.apvdberg.com