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Innovation and System Information

Research Results

Simulation of liquefaction-induced damage of the Port of Long Beach using the UBC3D-PLM model

This research studied numerically the detrimental effects of liquefaction-induced ground movements at the Port of Long Beach, which is vital for the California freight network.

Geotechnical/
Structures

OCTOBER 2016

Project Title:
Simulation of liquefaction-induced damage of the Port of Long Beach using the UBC3D-PLM model

Task Number: 2933

Completion Date: September 01, 2016

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WHAT WAS THE NEED?

Liquefaction-induced damage has been reported in numerous seismic events around the world: Alaska 1964, Japan 1995, Turkey 1999, Taiwan 1999, Iran 2004 and China 2008. Historically, Southern California has been seismically active for a radius of 300 km around the Port of Long Beach. At least 189 earthquakes were registered from year 1800 until present. The Port of Long Beach is located within a few miles of this fault line, and is also near the Newport-Inglewood and the Palos Verdes faults. The port has experienced significant expansion projects in the past decades which have been completed by placing hydraulic fill behind rock retention dikes. These man-made loose deposits have shown to be susceptible to liquefaction.

The abundance of quality field and laboratory testing performed in the port, which is the second busiest seaport in the United States, offered a unique opportunity to use advanced constitutive soil models for predicting the potential liquefaction-induced damage that the port could experience in future earthquakes. Most of the liquefaction studies from the port have been oriented to qualitatively discuss the effects of liquefaction but not to quantitatively demonstrate the phenomenon via advanced constitutive soil models and finite element programs. The port is an important transportation center moving a great variety of goods including but not limited to clothing, furniture, machinery, and petroleum.

WHAT WAS OUR GOAL?

The goal was to assess the performance of Pier S at the Port of Long Beach and determine if a seismic event induces liquefaction. Estimates of the permanent ground deformations were studied using numerical simulations and classical approaches to determine the resiliency of the port required for its immediate operation after a seismic event, and avoiding the disruption of the California freight network.

WHAT DID WE DO?

The following three main issues were answered in the analysis of the liquefaction susceptibility of the port: i) were the soils susceptible to liquefaction? ii) could liquefaction be induced by the earthquake motions under consideration? and iii) what are the potential consequences? To answer these questions, this research compiled in situ and laboratory tests, developed numerical simulations using advanced constitutive soil models of the advent of liquefaction, computed settlements using classical deterministic and probabilistic approaches, and issued recommendations resulting from the analyses. Soil parameters using advanced constitutive models like the UBC3D-PLM were calibrated after a compilation of published subsurface investigation reports of the Port of Long Beach. The calibrated soil parameters were used to reproduce at the laboratory scale the liquefaction phenomenon of loose sands under simulated cyclic direct simple shear conditions.

The scope of work of this research consisted of:

(1) Compilation of subsurface conditions including field and laboratory tests performed at Pier S of the Port of Long Beach, which served as the basis for the determination of the constitutive parameters of the UBC3D-PLM model to study soil liquefaction of the port.
(2) Development of advanced numerical analyses to study soil behavior during cyclic loading and recommendations for liquefaction effects at the Port of Long Beach. The long-term goal of these recommendations was to create a more resilient and sustainable port.
(3) Analysis of the soil behavior and response due to liquefaction at the proposed location using finite element analyses as well as the computation of the predicted soil response in light of other classical deterministic and probabilistic approaches.

WHAT WAS THE OUTCOME?

It was found that a highly compressible and cohesionless unit in the subsurface conditions was liquefiable under the two earthquake levels studied in this research: Operating and Contingency Level Earthquakes (OLE and CLE). The factors of safety against liquefaction lower than one (e.g., 0.3 for the CLE condition) represented a high likelihood of liquefaction to be induced in this site if an earthquake of such magnitude strikes the area. Semi-empirical triggering methods based on SPTs, CPTs and shear wave velocities confirmed that result. However, those methods are not intended to provide insight about post-liquefaction effects on soil or structures and that is the justification of the numerical analyses developed in this project.

Liquefaction-induced settlements using state-of-the-practice approaches were evaluated for free-field conditions. Using the results of SPTs, settlements of about 24 and 76 cm were computed for the OLE and CLE conditions, respectively. Using the CPTs, settlements of about 10 and 32 cm were computed for the OLE and CLE conditions, respectively. The numerical simulations showed that for the liquefiable layer, six different earthquake motions developed pore water pressure ratios larger than 85%, which caused significant reductions of the vertical effective stresses. Relative shear stresses computed for the liquefiable soil layer indicated that the OLE conditions were capable to mobilize about 70% of the soil shear strength. The CLE earthquakes mobilized almost the entire soil shear strength. Liquefaction mobilizes large amounts of shear strength and causes local failures in the soil mass.

Analyses of liquefaction-induced settlements for free-field conditions showed maximum settlements of 28 and 45 mm, respectively, after dissipation of excess pore water pressure generated during the cyclic loading.

Numerical simulations of 1, 2, and 3-story hypothetical structures founded on shallow footings on saturated granular soils suggested that most of the total liquefaction-induced settlements were caused during the earthquake motion with minor contribution arising from dissipation of the excess pore water pressure generated during the cyclic loading. Larger excess pore water pressures were generated under the analyzed hypothetical structures than those developed for the free-field conditions. For the liquefiable layer, the numerical simulations showed large values of earthquake-induced shear stresses that fully mobilized the soil shear strength especially in the zones located below the hypothetical structures. If predictions regarding liquefaction triggering and post-liquefaction behavior are needed, a combination of both methods (i.e., classical and advanced numerical methods) and a great amount of engineering judgement is advised.

WHAT IS THE BENEFIT?

This research presented an opportunity for advancing the understanding of the behavior of soils when liquefaction is induced. This project contributed to the understanding of the role of engineering on the resiliency of this vital port in the California freight network; the results directly influenced seismic design methods currently used in engineering practice. The educational impacts of this research were broad and inspired undergraduate and graduate students to develop research and draw design recommendations tended to understand and mitigate the effects of liquefaction on this port.

Although the proposed research was specifically aimed to study the resiliency of the Port of Long Beach after liquefaction, the fundamental concepts of the soil behavior developed in this project are also applicable to the construction of offshore structures, deep foundations, wharfs, and retaining structures. As a result, this research advanced the earthquake engineering design of these types of projects. This study indirectly helped to preserve the urban environment by providing further understanding of the liquefaction phenomenon needed to reduce the risk and improve the resiliency of these type of infrastructure projects.

LEARN MORE

To view the complete report:

https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/final-reports/ca16-2933-finalreport-a11y.pdf

IMAGES

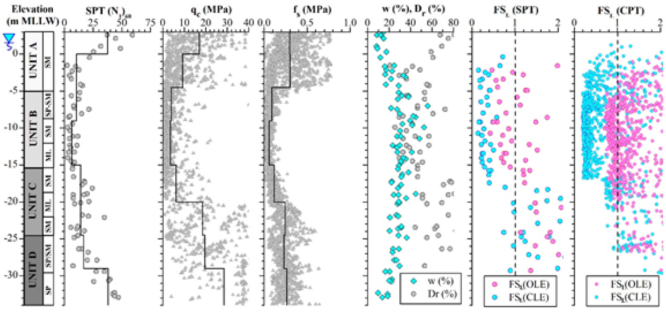

Image 1: Subsurface conditions at the project site

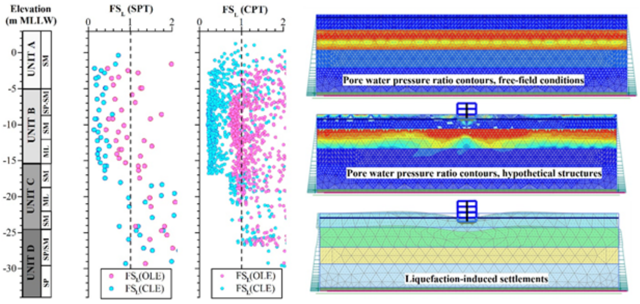

Image 2: Summarized soil profile, factor of safety against liquefaction and misc. program output contours

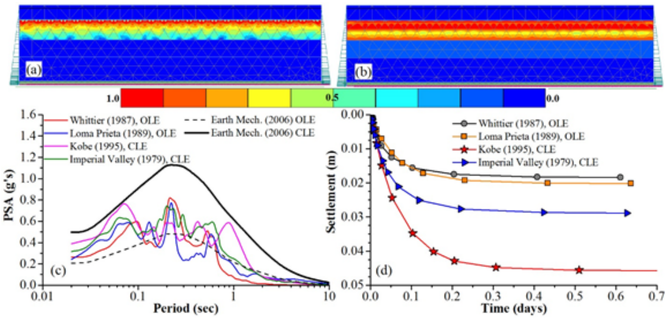

Image 3: Free-field numerical simulations: a) ru contours after Whittier 1987 (OLE), b) Imperial Valley 1979 (CLE), c) acceleration response spectra at the ground surface, and d) settlements computed from post-liquefaction dissipation of excess pore water pressures

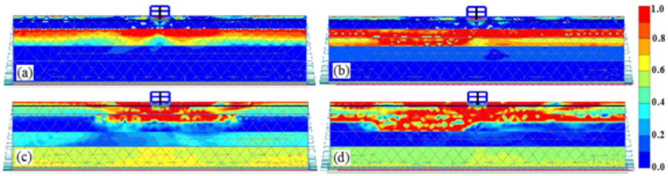

Image 4: Computed soil response of 2-story hypothetical structures at the site: a) ru contours for Whittier 1987 (OLE), b) ru contours for Imperial Valley 1979 (CLE), c) τrel. contours for Whittier 1987 (OLE), and d) τrel. contours for Imperial Valley 1979 (CLE)

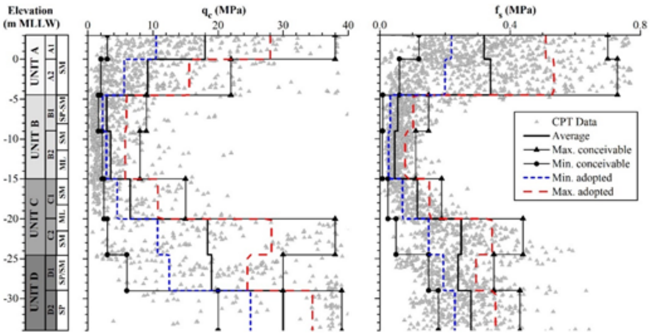

Image 5: Subsurface conditions at the project site and CPT test bounds used in the analyses

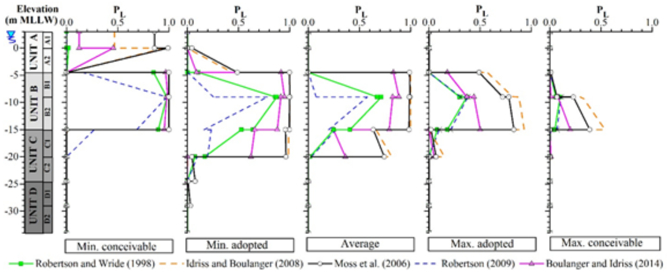

Image 6: Liquef. Probability curves for the set of CPT data: average, max. and min. conceivable and adopted

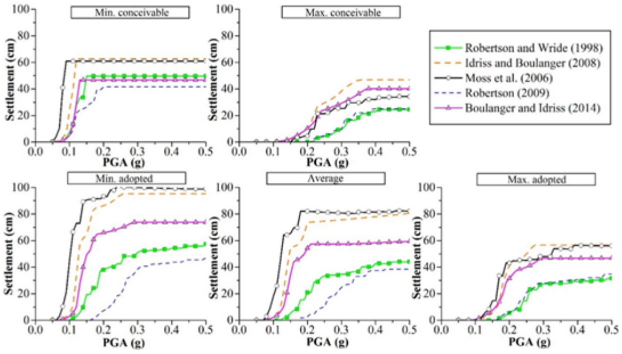

Image 7: Computed ground settlement for different PGAs for the set of CPT data: average, max. and min. conceivable and adopted

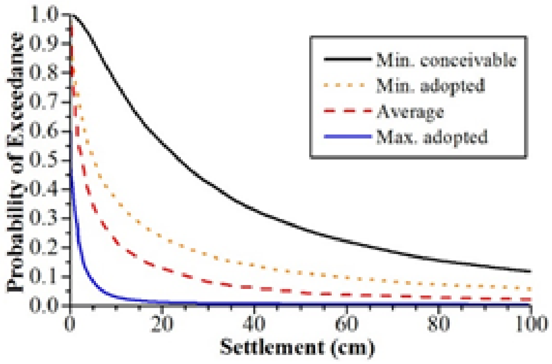

Image 8: Probability of exceedance of settlement for the set of CPT data