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LIQUEFACTION IN THE 2011 GREAT EAST JAPAN EARTHQUAKE: LESSONS FOR U.S. PRACTICE

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ABSTRACT: Liquefaction in the 2011 Great East Japan Earthquake will provide important lessons for the geotechnical profession regarding the seismic performance of a wide range of geotechnical and constructed facilities affected by liquefaction. This paper examines three aspects of observed liquefaction effects and discusses how they relate to current issues in geotechnical practice in the U.S. Potential opportunities for international group research efforts stemming from each of these examples are also discussed.

Key Words: Great East Japan earthquake, earthquake engineering, liquefaction, levees, strong ground motions

INTRODUCTION

Case histories of liquefaction in the 2011 Great East Japan Earthquake provide important opportunities for learning about the seismic performance of a wide range of geotechnical systems and constructed facilities affected by liquefaction. The opportunities for learning are particular strong because of the extensive network of strong motion recording stations and the volume of detailed data being compiled. The lessons learned from these case histories have implications for geotechnical engineering science and practice around the world.

Teams from the Geotechnical Extreme Events Reconnaissance (GEER) Association participated in geotechnical reconnaissance efforts with support and collaboration of numerous colleagues in Japan. A total of 25 GEER members worked with more than 26 Japanese counterparts in investigations of site response, liquefaction, levees, dams, ports, bridges, lifelines, recovery, and surface rupture (April 11 earthquake). Additional field work and analyses of the data by GEER members in collaboration with Japanese colleagues are ongoing.

This paper and the associated panel presentation will examine select aspects of liquefaction effects observed by GEER members (GEER 2011a, 2011b, 2011c, 2011d; http://geerassociation.org/) and Japanese colleagues (e.g., Ishihara et al. 2011, Tokimatsu et al. 2011), and discuss how they relate to some current issues for geotechnical practice in the U.S. The presented observations and examples of the potential lessons they offer are drawn from the above referenced GEER reports and from discussions with team members. Potential opportunities for future international research efforts stemming from each of these examples are also discussed.

LIQUEFACTION AND STRONG MOTION RECORDING STATIONS

Evidence of liquefaction was observed at seven strong ground motion recording stations in the Tokyo and Kanto Plain areas; photos of three of these sites are shown in Fig. 1. Another seven recording stations with soil profiles that would be considered susceptible to liquefaction did not exhibit surface evidence of liquefaction. The recorded motions at the ground surface show clear evidence of liquefaction in some cases, but in other cases the characteristics of the motions do not clearly exhibit any signs of significant softening or cyclic mobility during the time of strong shaking. The data from these sites with and without liquefaction will provide an excellent basis for evaluating the capabilities and limitations in one-dimensional nonlinear dynamic site response models.

GEER teams have assisted Japanese researchers with characterizing several of these sites using surface wave techniques (e.g., MASW and SASW) and arrangements have been made for cone penetration test (CPT) soundings at select sites. The sharing and on-line archiving of such data are an important component of earthquake reconnaissance activities. The volume of data regarding earthquake observations is growing rapidly, from seismology to sociology, such that systematic means for collecting, documenting, and mining such data also requires careful consideration and study.

(a)

(b)

(c)

Fig. 1 Sand boils at three strong ground motion recording stations (GEER 2011)

A number of different one-dimensional nonlinear dynamic site response programs are used in U.S. practice for estimating site response for liquefiable soil deposits. The results of such analyses are often used to estimate motions in overlying geotechnical or constructed systems or kinematic loading on embedded pile foundations. The constitutive models used for the liquefiable soils include some that can account for cyclic mobility behaviors while others can only monotonically soften with increasing pore pressure generation. Recent evaluations of these site response programs against recordings of the liquefaction arrays at Port Island during the 1995 Kobe Earthquake and Wildlife in the 1987 Superstition Hills Earthquake have illustrated that some of these programs produce unrealistic responses (e.g., Sideras 2011, Ziotopoulou et al. 2012). Some of these differences between recorded and computed responses for these two case histories are likely due to the combined influence of the approximations and limitations associated with 1D site response analyses (i.e., assumption of vertical propagation of shear waves in horizontally layered profiles), site characterization, soil properties, constitutive models, and numerical procedures. However, the differences in constitutive models are a major contributor to the more unrealistic responses. For this reason, further examination of these programs against the broader set of recorded data from the Great East Japan Earthquake can be expected to provide further illustration of important limitations in these programs, and thus contribute to the adoption of better standardized practices for assessing site response in liquefiable soil profiles.

An opportunity for an international group research effort would be the systematic evaluation of various 1D nonlinear site response programs and procedures against this body of data. The documentation of the simulation models, including the calibration and numerical procedure protocols, would be a valuable step for defining the potential limitations (bias and dispersion) in such models. The resulting database could present a lasting resource for evaluation of new simulation programs or modeling protocols as they are developed in the future.

LIQUEFACTION AND BUILDINGS IN URAYASU

Liquefaction at communities around Tokyo Bay and along the Tone River caused extensive damage to light residential and light commercial structures in many of the areas visited, with the magnitudes of the settlements and tilts for structures on shallow foundations being larger than often observed for such light structures. The photographs in Fig. 2 illustrate a case in Urayasu where the sidewalk and street settled approximately 30 cm relative to a building on piles, while an adjacent three-story building on a mat settled 40 cm more than the adjacent ground surface and tilted noticeably without observable damage to the superstructure. Tilts of up to 2 or 3 degrees were observed in many cases for residential homes (Fig. 3a). Many of the residential structures appear to have been founded on mat-type foundations with deep grade beams (Fig. 3b) that limited damage to the superstructures despite the large settlements and tilts.

Shallow foundations for light residential and commercial structures in U.S. practice are often comprised of shallow spread footings with grade beam connections and a concrete surface slab. These shallow foundation systems are not as stiff or strong as the example from Japan shown in Fig. 3b. Liquefaction of foundation soils can therefore cause significantly more deformation and distortion across the foundation system and into the structure. For example, the Moss Landing Marine Laboratory shown in Fig. 4 was destroyed when liquefaction during the 1989 Loma Prieta earthquake caused the foundation to stretch by about 1.0 to 1.3 m. Stronger and stiffer foundations in areas of potential liquefaction appear to be an effective means of protecting the structure from excessive distortions even when ground settlements are relatively large. Of course, there is still the damage to the underground utilities and the cost of leveling the structure after the earthquake, but this is less expensive than the complete loss of the structure.

Fig. 2 Differential settlements between a building on piles (gray building on the left), a building on a shallow foundation (brown building on the right), and the ground surface in Urayasu (GEER 2011)

Fig. 3 Tilt and settlement of a residential home in Urayasu (left photo) and a foundation for a residential home in construction (right photo) (GEER 2011)

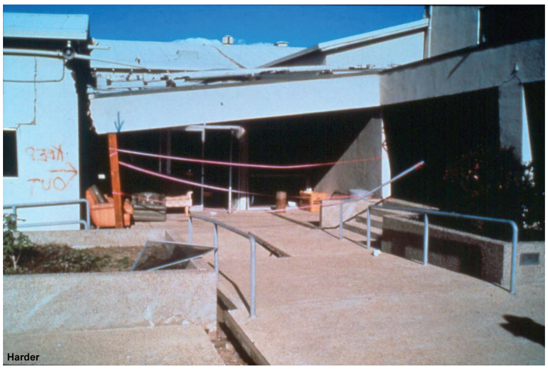

Fig. 4 Wood frame structure on shallow foundations nearly collapsed due to liquefaction-induced stretching of foundation by about 1.3 m in Loma Prieta earthquake (courtesy of L. F. Harder, Jr.)

Ishihara et al. (2011) report that SPT-based liquefaction analysis procedures do not appear to explain the differences in liquefaction-induced settlements across the various alluvial and fill materials of different ages and fines content in the Urayasu area. Resolution of such differences may require more basic research on the effects of ageing and fines content on liquefaction behavior and associated modifications to design procedures.

An opportunity for international group research would be the systematic evaluation of various engineering procedures for predicting liquefaction and liquefaction-induced settlements against this body of data. The comparison of engineering procedures against an established database would be a valuable step toward defining limitations and uncertainties (bias and dispersion) in the engineering procedures used in different countries. The resulting database would present a lasting resource for the future updating and development of engineering procedures as our knowledge and understanding of liquefaction phenomena improves.

Liquefaction-induced damage to utilities caused widespread disruptions for homeowners and businesses and is an important consideration for any urban area. Recent experiences from New Zealand have demonstrated the tremendous ability of HDPE and MDPE pipes to withstand significant ground deformations associated with liquefaction (O'Rourke, personal communication). The compilation of experiences from urban areas such as Urayasu will provide further data to define fragilities of different types of piping systems. The combined lessons are expected to have an important effect on the future practices in the U.S. and could similarly be of interest to many countries.

LIQUEFACTION AND LEVEES

It appears that the majority of the levee reaches along the rivers in the Tohoku and Kanto regions performed well, with the large majority of their lengths exhibiting little or no damage or distress. This generally good performance may be partly attributed to the fact that river levels were relatively low at the time of the earthquake and thus the majority of levee embankments were not saturated. In many areas, settlements of non-distressed levees appeared to be less than about 15 cm relative to structures such as bridge piers or buried water conveyance structures.

Nonetheless, numerous levee reaches sustained moderate to major damage (e.g., Fig. 5) which appeared to be related to foundation liquefaction. Settlements of 20-40 cm were observed in many areas, with greater settlements in reaches of relatively limited lengths (commonly only 100-300 m in length). Little or no flooding appeared to have resulted from the damage to the levees since water levels were low within the adjacent channels.

Levees along the Hinuma River had extensive damage from foundation liquefaction (Fig. 6). These levees were apparently founded on reclaimed land, and developed extensive cracking and slumping for over 2.5 km along the western margin of the shallow, near-coastal lake. New fill had been placed after the earthquake into some reaches where it appeared that the water might breach the slumped levee. The extensive damage to these levees, as opposed to the more limited (but multiple) damaged reaches of levees in other locations, appears to reflect the presence of man-made foundation materials or of water levels high enough to saturate both the foundation and the lower portions of the embankment. In some sections, the water level appeared to be about a meter higher than the landside ground surface. Exposed embankment material in the numerous large cracks indicated that the upper fill was composed of clayey sands and gravels. However, the numerous sand boils found in the cracks were generally clean, fine to medium-grained sands, which would be consistent with the underlying foundation being reclaimed land or fills. The length of liquefaction damage has significant implications for saturated levees constructed of or on dredged material, such as those in the Sacramento-San Joaquin Delta in California's Central Valley.

The performance of four levee reaches on improved ground along the Naruse River was examined. These levee reaches had previously experienced major liquefaction damage during the 2003 Miyagi North Continuation Earthquake (M_w 6.2) and had been repaired with a mix-in-place soil cement foundation treatment. All four sites appeared to have performed well with no observable damage from the apparently stronger 2011 earthquake shaking. Notably, two of these sites had moderate liquefaction-related levee damage directly beyond the limits of the ground treatment (Fig. 7a). In some cases, this resulted in significant transverse cracks along the transition boundary between the treated and non-treated sections of the levees (Fig. 7b). Such transverse cracking may be expected where the foundation stiffness of adjacent levee sections has abrupt, dramatic changes. Transverse cracks between treated and non-treated levee reaches may be an issue that needs to be considered carefully because such cracks have the potential to lead to failures by seepage erosion through the cracks if the adjacent water levels are high enough and the levee is not designed with internal details that minimize the potential for such erosion failures.

Fig. 5 Levee Damage along Naruse River Left Levee at River Kilometer 11.3 (GEER 2011b,d)

Fig. 6 Views of Hinuma River Levee Slumped and Cracked Due to Liquefaction (GEER 2011b,d)

Fig. 7 View of Treated and Untreated Levee Reaches along Naruse River Right Levee at River Kilometer 15.0 - 14.7 (previously treated section in the distance; left photo). Transverse Crack at Boundary between Treated and Untreated Levee Reaches (right photo) (GEER 2011b,d)

The seismic performance and recovery of the levee systems throughout the affected regions are of interest to ongoing seismic studies of levee systems throughout California. California has significant seismic concerns for the levees protecting various urban areas and the vital Sacramento-San Joaquin Delta (Fig. 8). A large portion of the Delta is comprised of "islands" which are ringed by levees and whose land surfaces are below the level of the adjacent waterways (e.g., Fig. 9). The hundreds of km of levees protecting these islands are therefore continuously holding back waters. Static failures of the levees periodically lead to flooding of the islands (e.g., Fig. 10), which can have a detrimental effect on water quality for the State. Failure of multiple levees during a seismic event is a major concern for the State of California due to its environmental and economic impacts.

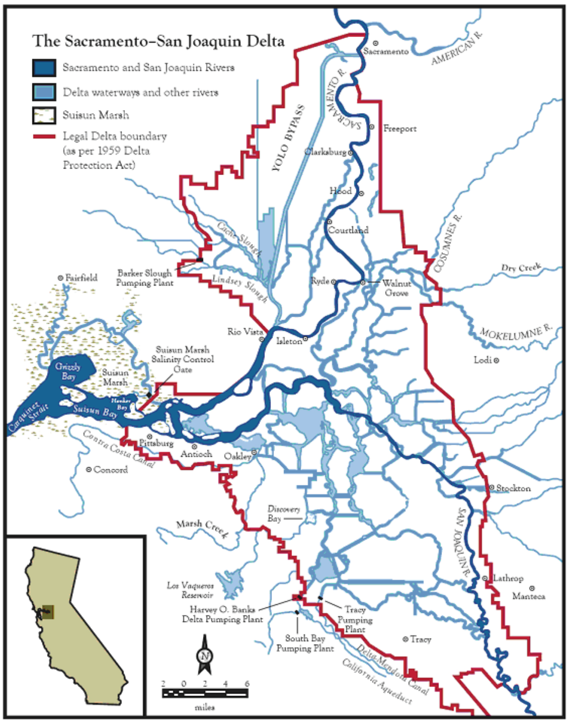

Fig. 8 Sacramento-San Joaquin Delta in California (Lund et al. 2007; Copyright by Public Policy Institute of California)

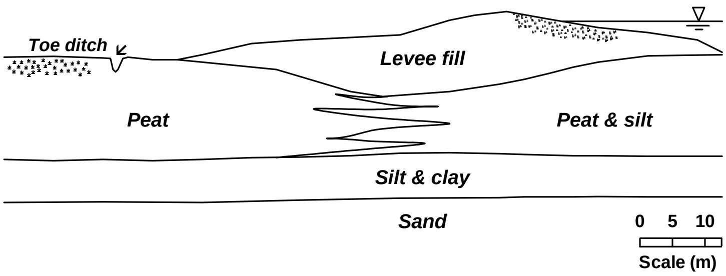

Fig. 9 A levee cross-section from Sherman Island (Boulanger and Kishida 2007)

Fig. 10 Photographs from the Jones Tract failure in 2004 (photo courtesy of L. F. Harder, Jr.)

Statistics from Japan on the distribution of levee damage relative to geologic and constructed conditions can provide a basis for examining the procedures that are used to develop levee fragility functions and assess the extent of damage across a system. These patterns of damages (and their relation to the geology), the performance of improved sections, and the associated practices for achieving rapid recovery offer potentially important lessons for California's levee systems. The disaster in New Orleans and recent work on an International Levee Handbook illustrate the strong international interest in sharing practices and understanding of levee systems. The experiences from Japan could present an opportunity for an international group effort on exchanging and comparing procedures used to assess the seismic response of levee systems and respond to seismic damages.

CONCLUDING REMARKS

The ongoing studies of liquefaction in Great East Japan Earthquake are likely going to have a major impact on the science and engineering of liquefaction. The quantity and quality of data being compiled in Japan: (1) provides unique opportunities for quantifying potential bias and dispersion in the various analysis methods used to predict responses for a broad range of systems and (2) appears to indicate some unexpected behaviors that require further study. Documentation and archiving of these data in a form that facilitates their utilization by future researchers will be a lasting contribution to the advancement of the science and engineering of liquefaction problems.

The experiences and data compiled from this earthquake offer some unique opportunities for stimulating international group research efforts. This paper briefly discussed observations regarding strong ground motion recording stations underlain by liquefiable soils, liquefaction and buildings in Urayasu, and levee damages due to liquefaction. Each of these example problems have important connections to problems in U.S. geotechnical practice and could be the basis for coordination of international group research efforts which could produce significant advances for international practices. Other aspects of liquefaction in this earthquake, while not discussed herein, offer similar opportunities for significant advancements.

Societal risks associated with the presence of pervasive liquefaction hazards and larger than considered ground motions need to be better understood and recognized so that appropriate decisions can be made by at-risk communities and regions. The recent experiences with liquefaction in Japan and New Zealand have made the risks to communities very clear and provide an opportunity for improving public policies in various countries facing similar risks.

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