29 May 2010, 8:05 am - 8:25 am

# General Report — Session 8

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Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
*and Symposium in Honor of Professor I.M. Idriss*
May 24-29, 2010 • San Diego, California

# GENERAL REPORT SESSION 8: MODEL AND FULL-SCALE TESTS OF GEOTECHNICAL STRUCTURES INCLUDING CENTRIFUGE TESTS, RECENT ADVANCES FROM EARTHQUAKE SIMULATION FACILITIES SUCH AS NEES, E-DEFENSE, NCREE

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## OVERVIEW OF SESSION

Session 8 focuses on presenting results from model and full-scale tests on geotechnical structures, as well as finite element analysis and case histories of geo-structure performance. This General Report summarizes the 14 papers accepted for presentation during the session. The papers originate from eight countries: Canada, Germany, Greece, India, Japan, Taiwan, United Kindom, and the United States. Topics presented include pile foundations, liquefaction, underground structures (e.g., tunnels), retaining structures, and ground improvement. Although the title implies all papers are focused on testing results, two of the papers focus solely on numerical simulation or data analysis, and many of the experimental papers include detailed numerical modeling efforts. The Table below lists the paper number, author(s), title, general topic, and test facility utilized (if applicable) for each of the papers. Subsequently, a general overview of each paper is provided to direct the reader to areas of interest.

| Paper | Authors | Origin | General Topic | Test Facility |
|---|---|---|---|---|
| 8.01 | Hemeda, Bkasis, Pitilakis | Greece | Numerical modeling, underground structures | N/A |
| 8.02 | Dube | India | Rock pressures, Case history | N/A |
| 8.04 | Chen and Ueng | Taiwan | Soil-pile interaction in liquefied soil, shake table tests | NCREE, Taiwan |
| 8.05 | Khokher and Madabhushi | United Kingdom | Retaining structures, earth pressure measurement, centrifuge tests | Cambridge University, Centrifuge Facility |
| 8.07 | Sato and Tabata | Japan | Liquefaction, port structures, shake table tests | E-Defense, Japan |
| 8.08 | Chou and Kutter | USA | Tunnels, centrifuge tests | NEES-UC Davis |
| 8.09 | Olson, Hashash, Muszynski, Phillips, and Polito | USA | Earth pressures, measurement methods, centrifuge tests | NEES-RPI |
| 8.10 | Sato, Tabata, and Abe | Japan | Liquefaction, port structures, shake table tests, centrifuge tests | NIED, Japan |
| 8.11 | Beena | India | Stone columns, geotextile-encasement, laboratory testing, quarry dust | Cochin University, India |
| 8.13 | Zarnani, Bathurst, and Take | Canada | Geo-synthetic reinforced soil retaining walls, shaking table tests | Royal Military College of Canada |
| 8.14 | Chang and Hutchinson | USA | Soil-pile interaction in liquefied soil, shake table tests | UCSD |
| 8.17 | Ozcelik, Luco, Conte, and Mendoza | USA | Soil-structure-interaction, attenuation, shake table tests | NEES-UCSD |
| 8.18 | Nakazawa, Sugano, Shinsaka, Adachi, and Yamada | Japan | Liquefaction, improved ground, field testing | Field site, Ishikara Bay Port, Hokkaido Island, Japan |
| 8.20 | Wienbroer, Rebstock, and Huber | Germany | Numerical modeling, liquefaction, shake table tests | University of Karlsruhe, Germany |

SUMMARY OF INDIVIDUAL PAPERS

**Paper 8.01**
**Title:** Three-dimensional stability analysis of the central rotunda of the catacombs of Kom El-Shoqafa, Alexandria, Egypt
**Authors:** Hemeda et al.
**General Topics:** Numerical modeling, underground structures

The authors present an interesting finite element analysis of the central rotunda of the Kom El-Shoqafa catacombs using advanced 3D finite element modeling software. The results are well-presented, however several items warrant additional discussion, including: (1) explaining situations where an advanced 3D finite element analysis is needed to compute vertical stress in the rock pillars and when simple hand calculations yield accurate vertical stresses; (2) explaining the differences of the 2D and 3D computations for vertical stress; (3) presenting the measured surface settlements (and explaining how settlements of less than 3mm were accurately measured and confirmed) that were used to validate the results of the 3D finite element analysis; and (4) presenting how the model parameters were derived from the field and laboratory testing.

**Paper 8.02**
**Title:** Assessment of rock pressure for tunnels in the Himalayan region – a case history
**Authors:** Dube
**General Topics:** Rock pressures, case history

The author summarizes analytical and experimental rock pressure information dating back to the late 1930s. Analytical methods focus on simple empirical rock mass classification approaches. Instrumented installations in two tunnels excavated through thrust belts in the Himalayan Mountains are presented. Cross-comparison of the various data is provided via tabular format. Via comparison with field data, the literature review indicates that the methods considered for estimating rock pressures do not provide sufficient accuracy. Empirical pressure could be higher or lower than observed pressures, in some cases by an order of magnitude (conservative or unconservative). The author then surmises that the current thinking that underground structures (such as tunnels) are less vulnerable to the effects of earthquakes is questionable. He indicates that this should be considered in light of the uncertainty associated with rock pressure estimates. Review of the seminal work by Wang or others, which provide clear explanations of why underground structures generally fare better than surface structures during earthquakes should be considered.

**Paper 8.04**
**Title:** Behavior of model piles in a liquefiable soil in shaking table tests
**Authors:** Chen and Ueng
**General Topics:** Soil-pile interaction in liquefied soil, shake table tests

Two model piles of different material were separately tested in a saturated sand in a large biaxial laminar shear box and subjected to base shaking at the National Center for Research on Earthquake Engineering, Taiwan. One pile was constructed of stainless steel pipe, while a second pile was constructed of aluminum alloy pipe. As a result the second pile had an EI of less than half the first. The authors describe the experimentally observed interaction between the two piles with different moduli during dynamic loading. Although conceptually understood, the authors' results provide clear evidence of the influence of pile stiffness, soil stiffness (before and after liquefying), and superstructure mass on the dynamic response of the pile. These results, as well as the future research proposed by the authors, could provide a basis for seismic design of piles installed in level ground where liquefaction is predicted to occur. Moreover, results from such testing will be useful for validating numerical tools for use in design and analysis of pile-supported structures in liquefaction prone areas.

**Paper 8.05**
**Title:** Dynamic earth pressures and earth pressure cell measurements
**Authors:** Khokher and Madabhushi
**General Topics:** Retaining structures, earth pressure measurement, centrifuge tests

In this paper, the authors examine the development of dynamic earth pressures against flexible and more rigid retaining structures during seismic shaking using centrifuge testing. This topic is important given the recent uncertainty in the level of conservatism provided by classical methods such as that of Mononobe-Okabe (M-O). Unique to these tests are that the authors directly measure the dynamic earth pressures at discrete locations using miniature earth pressure cells. Three centrifuge tests were conducted at 80-g, considering variations in wall height and retaining wall thickness (stiffness). All tests were conducted in medium-loose (Dr ~ 50-60%) dry sand. The authors find that the M-O method overpredicts retaining wall seismic-induced earth pressures for peak ground accelerations greater than 0.2g's. In addition, evaluation of the earth pressure cells indicate that their accuracy is limited to qualitative assessment only, and reliable quantitative measurements could not be obtained. The influence of wall height on the authors' conclusions may be of interest in future study of the data.

**Paper 8.07**
**Title:** E-Defense shaking table test on the behavior of liquefaction-induced lateral spreading of large-scale model ground with a pile-foundation structure behind quay wall
**Authors:** Tabata and Sato
**General Topics:** Liquefaction, port structures, shake table tests

The authors describe an impressive full-scale model of a realistic port structure tested at the E-Defense facility in Japan. The testing involved multiple structures (quay wall, footing, and pile foundation) and over 900 instruments. All aspects of the experiments are impressive due largely to the pure size of the specimen and extensive instrumentation. The specimen was subjected to biaxial shaking, using a record from the 1995 Kobe earthquake. The intense shaking caused liquefaction in all layers, which instigated overturning of the quay wall and lateral spreading. Subsequently the pile foundation deformed severely towards the water-side of the model. Such results are similar to failures observed during previous earthquakes. The data set produced by this set of experiments will prove useful for calibrating numerical models for use in design of pile-supported structures, particularly those near waterways.

**Paper 8.08**
**Title:** Numerical analyses of centrifuge models of the BART Transbay tube
**Authors:** Chou et al.
**General Topic:** tunnels, numerical modeling, centrifuge tests

The authors describe their 2D finite element modeling (FEM) of liquefaction occurring in sand backfill around an immersed tube tunnel. The FEM is compared to centrifuge models performed at the NEES facility at UC-Davis. Two different centrifuge tests were performed, with their difference being the characteristics of the trenched material below the tunnel, one being low plasticity clay, the other high plasticity lightly overconsolidated clay. The authors provide some centrifuge test results used to validate the 2D FEM, and describe the numerical model in sufficient details to provide confidence in their results. Importantly, the authors identify compromises needed to optimize computing time, model convergence, and agreement with the centrifuge experiment results. Comparison with the centrifuge experiments focuses on (1) tunnel movement; (2) deformation patterns of the soil; and (3) pore pressures across the bottom of the tunnel. Results from the FEM match the trends of the centrifuge model reasonably well; however as noted by the authors, the magnitude of movements and porewater pressures are overestimated by the FEM.

**Paper 8.09**
**Title:** Using tactile pressure sensors to measure lateral spreading-induced earth pressures against a large, rigid foundation
**Authors:** Olson et al.
**General Topic:** Earth pressures, measurement methods, centrifuge tests, liquefaction

The authors present a detailed study of the performance of tactile pressure sensors for use in centrifuge testing. The study aims to develop a methodology for using the sensors in liquefaction-induced lateral spreading tests on large, rigid foundation structures. The focus of this paper however is on the instrumentation and documenting its performance. The authors walk through the techniques tested to increase confidence in the quantitative pressure values obtained from the sensors. For this reason, for example, one aspect of the presentation involves executing 1-g shear box tests under reasonably well defined condition to evaluate the effects of shear stress on the measured normal stresses. These tests present for the first time the use of tactile sensors in a saturated soil, dynamic centrifuge environment. The authors summarize key aspects that must be considered to support a high level of confidence in the pressure sensor data, namely: (1) reduction of the friction at the pressure sensor pad; and (2) conditioning of the sensor, while in-place (i.e. in the centrifuge) prior to shaking.

**Paper 8.10**
**Title:** Large-scale shake table test on lateral spreading of sheet-pile wall model and its centrifuge simulation
**Authors:** Sato et al.
**General Topics:** Liquefaction, port structures, shake table tests, centrifuge tests

In this paper, the authors describe a study similar to that described in Paper 8.07, which involved large-scale shaking table testing of a pile-founded structure located behind a caisson-type quay wall. In this parallel study, the authors performed a large-scale shaking table test involving a pile-founded structure behind a sheet-pile wall and a dynamic centrifuge test at 15-g with like conditions to simulate the large-scale test. The authors present relevant results from both experiments and illustrate the reasonable agreement between the two experiments. One interesting aspect of the experiments is that porewater pressures appear to begin dissipating faster in the centrifuge test than in the large-scale test, although complete dissipation occurs in about the same length of time in both experiments. Another interesting observation is that the majority of lateral movement of the sheet-pile wall occurs well after the end of shaking, as a significant percentage of the porewater pressures are dissipating. Similar behavior is observed in the centrifuge test. In contrast, much smaller movements are observed after shaking in the centrifuge experiment. Finally, similar to the results in Paper 8.07, the data set produced by this experiment will prove useful for calibrating numerical models for use in design of pile-supported structures, particularly those near waterways.

**Paper 8.11**
**Title:** Model Studies on Stone Columns
**Author:** Beena
**General Topics:** stone columns, geotextile-encasement, laboratory testing, quarry dust

The author describes the improvement in load-settlement behavior of stone columns when encased in a geotextile. In a second round of laboratory testing, the author replaced the stone in the geotextile-encasement with various percentages of quarry dust. In the latter testing, the author found that using replacing 30 to 100% of the stone with quarry dust (when still using geotextile encasement) did not reduce the load-carrying capacity of the geotextile-encased "stone" column significantly compared to a geotextile-encased stone column with 100% stone. These results illustrate that it may be possible to replace the stone with less costly materials if the column is encased with a geotextile.

**Paper 8.13**
**Title:** Shaking table methodology and instrumentation for reinforced soil retaining walls
**Authors:** Zarnani et al.
**General Topics:** geosynthetic-reinforced soil retaining walls, shaking table tests

The authors present test details and results for a large scale shaking table experiment conducted on a reinforced soil retaining wall. The tests are conducted on a new friction bearing-based uniaxial shake table at the Royal Military College of Canada. The wall is of a reasonably large size with height of 1.42m, and interestingly the test program involves use of a number of different instruments including Particle Image Velocimetry (PIV) to capture deformation patterns of the soil and facing units. Sixty-mm square patches across the elevation of the model, with a precision of about 0.1mm were tracked using PIV. Experimental results are presented in terms of the walls facing movement pattern, peak acceleration pattern, acceleration amplification, and strains within the geogrids. In comparing the PIV data with the analog sensors, the authors observe near perfect agreement of the facing movement of the wall. On-going findings of these experiments may lead to modifications in wall, backfill soil, and reinforcing detailis, which in turn should improve wall design.

**Paper 8.14**
**Title:** Experimental Investigation of Plastic Demands in Piles during Lateral Spread-Induced Loads
**Authors:** Chang and Hutchinson
**General Topics:** Soil-pile interaction in liquefied soil, shake table tests

In this paper, the authors describe full-scale shaking table tests of a single pile embedded performed in a mixed soil with a non-liquefiable cap soil, a liquefiable sand, and a dense sand foundation. The authors describe the results of the shaking table tests in terms of shaking-induced excess porewater pressures and lateral spreading displacements, as well as the moments and curvature in the pile. These results compare favorably with pile behavior observed in centrifuge tests reported in the literature and with the behavior of real structures. The full-scale results reported in the paper will prove useful for validating centrifuge and numerical models of pile performance in laterally-spreading soils.

**Paper 8.17**
**Title:** Experimental study of the dynamic interaction between the foundation of the NEES/UCSD shake table and the surrounding soil
**Authors:** Ozcelik et al.
**General Topics:** Soil-structure-interaction, attenuation, shake table tests

The authors describe a study to evaluate geophysical and dynamic geotechnical conditions around the NEES-UCSD shake table facility. Data is needed for large numerical modeling of the facility systems, to evaluate site response characteristics to validate soil-structure interaction analysis methods, and to validate the unconventional design of the facility which utilizes the stiffness of the existing ground to reduce the weight and cost of the foundation system. The site and foundation system was thoroughly instrumented and a number of vibration tests conducted over a range of frequencies was performed. Based on the results of the tests, the authors provide a fairly complete description of the dynamic properties of the facility and validate the unconventional design of the facility foundation.

**Paper 8.18**
**Title:** Investigation of the coefficient of earth pressure for improved ground by compaction grouting in the full-scale field liquefaction experiment
**Authors:** Nakazawa et al.
**General Topics:** Liquefaction, improved ground, field testing

The authors present an interesting blast-induced liquefaction field experiment conducted on Hokkaido Island in Japan. The experiment was designed to study countermeasures used to minimize liquefaction-induced damage at airport facilities. For this reason, a large model airport runway was constructed (50mx60m in plan), and various ground improvement techniques implemented at the runway site. Techniques used included compaction and permeation grouting. Results in this paper focus on the compaction grouted regions. Effectiveness of the countermeasure was evaluated via physical observations prior to the blast, immediately following the blast, as well as following dissipation of blast-induced excess pore pressure in terms of standard penetration test data and earth pressures. In general, the authors found that the standard penetration test values increased in areas improved using the proposed strategy.

**Paper 8.20**
**Title:** Numerical and experimental investigation of soil behavior under stationary excitation
**Authors:** Wienbroer et al.
**General Topics:** Numerical modeling, liquefaction, shake table tests

The authors present a numerical model and comparative experimental program focused on evaluating ground response under sinusoidal motions. Using controlled increases in velocity-amplitude and frequency, the numerical model is exercised and results generated describing the amplification of a generalized one-dimensional soil column. The study is continued using a smooth laminar box restricted to only shear modes of deformation, filled with both dry and saturated sand. The authors present transient pore pressures and soil surface settlements under increased amplitude sinusoidal motions imposed on the physical model. Results clearly demonstrate cyclic mobility and liquefaction of the soil column physical model.

FINAL REMARKS

The papers presented in this session cover a wide range of important topics in the area of geotechnical earthquake engineering. An emphasis of most of the papers is on careful documentation of field or laboratory experiments and identification/quantification of the physical mechanisms observed. Such papers should prove extremely useful for calibrating and developing new numerical and analytical modeling tools for use in future design/analysis efforts.

TOPICS FOR DISCUSSION

1) Validation of numerical models using experimental data
2) Accounting for effects of earthquake-induced liquefaction on foundation systems
3) Ground improvement methods for mitigating liquefaction and ground shaking damage
4) Comparison between 1-g and centrifuge shaking tests to evaluate performance of geo-structures during earthquakes
5) Dynamic soil-structure-interaction and its effects on geo-systems
6) Earthquake- and liquefaction-induced earth pressures on foundation systems
7) Novel measurement systems for evaluating liquefaction-induced earth pressures

ACKNOWLEDGEMENTS
We extend our many thanks to Professor Shamsher Prakash for his leadership in the architecture and execution of this conference. We also thank Ms. Lindsay Bagnall for her organization of the proceedings and keeping us on track. Special thanks to Ms. Barbara Chang of UCSD for the additional comments regarding Paper 8.04. The Chairman (Prof Pitilakis), Co-Chair (Prof Stokoe), and Discussers (Phillips, Profs Brandenburg and Beena) of Session 8 are thanked for their contributions to the success of the meeting. Finally, importantly the many authors in this session are thanked for their excellent contributions to the literature.