Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-3117

Technical session 4b: Earthquake related problems

Séances techniques 4b: Problèmes liés aux tremblements de terre

R.W. Boulanger
Department of Civil and Environmental Engineering, University of California, Davis, USA

1 INTRODUCTION

There were 28 papers in the session on Earthquake Related Problems. Twenty papers deal with liquefaction problems, six papers deal with site response, zonation, and fault rupture problems, and two papers deal with slope stability and earth pressure problems. The liquefaction-related papers can be further grouped into those that primarily address the behavior of various soil types (seven papers), the effects of repeated and irregular cyclic loading (three papers), the performance of foundations (three papers), field studies and testing of field samples (four papers), and remediation (three papers). Each paper is briefly summarized, followed by a few general comments.

2 LIQUEFACTION

2.1 *Various Soil Types*

Yamashita, Ito, Hori, Suzuki, and Murata describe a detailed study of the "Geotechnical properties of liquefied volcanic soil ground by 2003 Tokachi-Oki earthquake." This case history involved a flow slide of about 10,000 m^3 of volcanic ash fill that was triggered by this magnitude 8 earthquake producing a peak ground acceleration of about 0.12 g at the site (Fig. 1). The site was investigated using in situ tests (Swedish weight sounding, cone penetration, mini dynamic penetration, & spectral analysis of surface waves tests) and undrained cyclic triaxial and bender element (shear wave velocity) tests on undisturbed field samples and reconstituted specimens. The different approaches were reasonably consistent in demonstrating the volcanic ash fill had relatively low cyclic strengths. It was further inferred that the roughly 20 years of ageing had not produced significant increases in stiffness or cyclic strength for this fill soil.

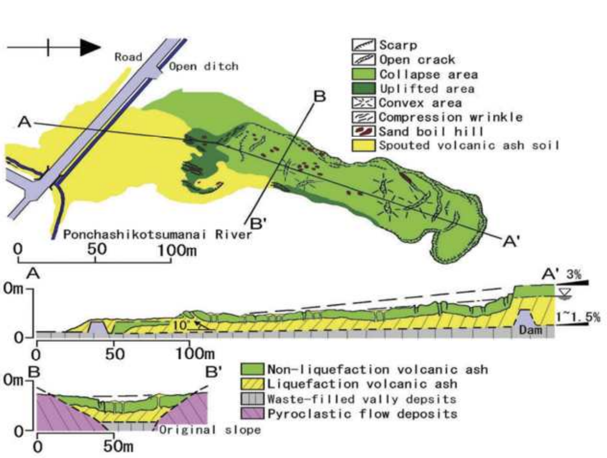

Figure 1. Schematic of volcanic ash flow slide (Yamashita et al.)

In related papers, Fleureau, Hadiwardoyo, and Kheirbek-Saoud present a laboratory study of the "Seismic sensitivity of a dam material" while Brenner, Wieland, and Malla describe the "Large-diameter cyclic triaxial tests for seismic safety assessment of an earth dam." Cyclic and static triaxial tests on 300-mm-diameter compacted specimens were performed for the morainic, non-plastic soil (scalped at 50 mm) taken from the core of a dam. The cyclic triaxial specimens were anisotropically consolidated with the ratio of major to minor principle effective stresses being $K_c = \sigma_{1c}'/\sigma_{3c}' = 2.86$ to 4.25. Subsequent cyclic loading did not produce shear stress reversal (i.e., a temporary state of isotropic stress), and so excess pore water pressure ratios (r_u) never approached 100% in these apparently dense specimens (Fig. 2). The specimens nonetheless did developed substantial strains (well in excess of 5%), which was subsequently considered in the estimation of dam deformations.

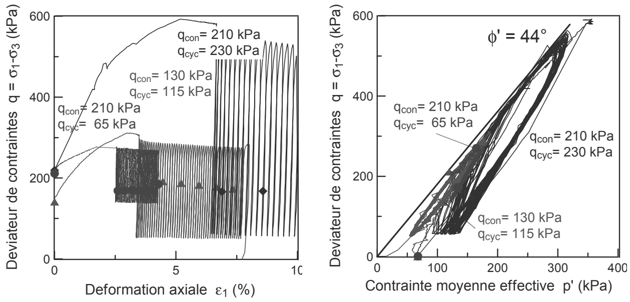

Figure 2. Large-diameter cyclic triaxial tests on anisotropically-consolidated non-plastic morainic soil (Fleureau et al.)

Laue and Buchheister discuss "Load path and loading velocity as potential condition indicator for liquefaction of silty soils." They introduce a dimensionless parameter that combines the cyclic stress ratio, hydraulic conductivity and loading frequency, and attempt to relate this parameter to liquefaction phenomena in various soils without success. Hydraulic conductivity is known to play an important role in liquefaction phenomena in the field, but future efforts in this direction may benefit from dimensional forms that are more directly related to the diffusion/consolidation of excess pore water pressures.

Huang, Huang, and Ho describe a detailed study for "Assessment of liquefaction potential for a silty sand in Central Western Taiwan." Correlations were developed between the soil's cyclic resistance ratio (CRR), CPT tip resistance, and shear wave velocity for both in situ and reconstituted soils. The correlation for reconstituted soils was developed based on a program of CPT calibration chamber tests and cyclic triaxial tests with bender element measurements of shear wave velocity. The correlation for in situ soils was developed based on in situ SPT, CPT and V_s measurements and cyclic triaxial tests (with bender element measurements) on high-quality field samples. The resulting correlations indicated greater cyclic strengths than would be predicted by common correlations to the CPT penetration resistance or V_s values (e.g., Fig. 3). The results also suggested that the effect of fines content on the CRR-q_{c1N} correlation only becomes important once the fines start affecting the drainage conditions around the CPT tip (which they suggest was at about 30% fines for their tests). A particularly interesting aspect of these results is that the plasticity index (PI) values for these soils were in the range of 7 to 14, which is sufficiently plastic that their behavior would likely be considerably different from that for nonplastic fines (e.g., Boulanger and Idriss 2004).

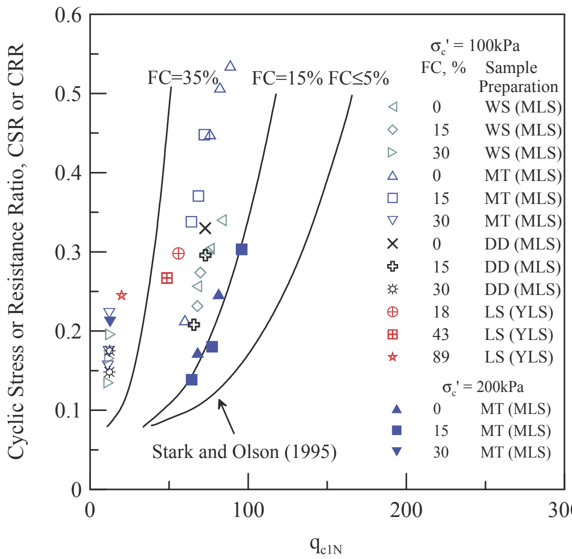

Figure 3. Correlation between CRR and q_{c1N} for a silty sand from Central Western Taiwan (Huang et al.)

Van Laak and Ng investigated the seismic stability of completely decomposed granite (CDG) in "Stability of loose CDG fill slopes subjected to uni-axial and bi-axial earthquakes in a centrifuge." The CDG material classifies as well-graded silty sand. The centrifuge tests were comprised of submerged model slopes of loose CDG subjected to either horizontal sinusoidal shaking or combined horizontal-vertical sinusoidal shaking (Fig. 4). Maximum excess pore pressure ratios of 70% to 87% were reported for shaking events with peak base accelerations of about 0.3 g. The fact that excess pore pressure ratios never reached 100% could be attributable to the initial static shear stresses being large enough that the total shear stresses during shaking (static plus cyclic) were always greater than zero (recall that r_u=100% only occurs when a soil is under an isotropic state of stress); For example, consider the cyclic triaxial test results by Fleureau et al. shown in Figure 2. The crests of the 5.7-m high (prototype) model slopes experienced settlements of 0.28 m during horizontal shaking (versus 0.26 m of static settlement during spin-up) and 0.34 m during combined horizontal-vertical shaking (versus 0.35 m during spin-up). The authors conclude that loose CDG slopes are likely to be stable for the design earthquake loading in Hong Kong.

Sitharam, Ravishankar, and Raju investigated the "Deformation characteristics of sandy soils subjected to cyclic loads," wherein they evaluated shear modulus and equivalent damping ratios for Ahmedabad sand (10% nonplastic fines content) prepared at a broad range of saturation levels (from dry to fully saturated) and tested at medium to large strain levels. The secant shear modulus was higher for samples at about 10% saturation than for dry or more saturated samples, which is consistent with the expected effects of capillary tension at low saturation levels and excess pore pressure generation at higher saturation levels (Fig. 5). Equivalent damping ratios were slightly higher in dry sands than in partly saturated or saturated sands. Other findings were also generally consistent with existing literature.

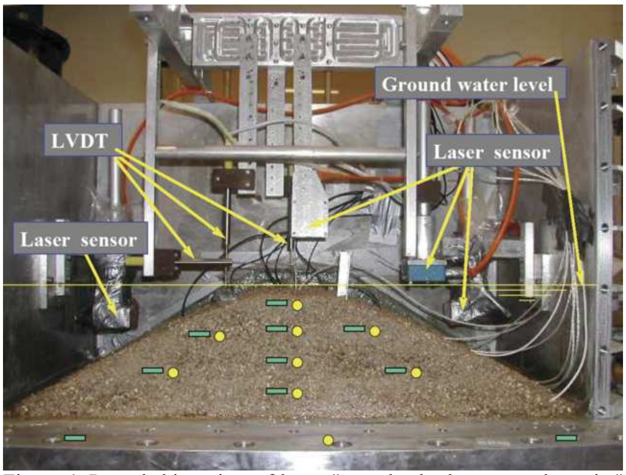

Figure 4. Post-shaking view of loose "completely decomposed granite" fill slope (Van Laak and Ng)

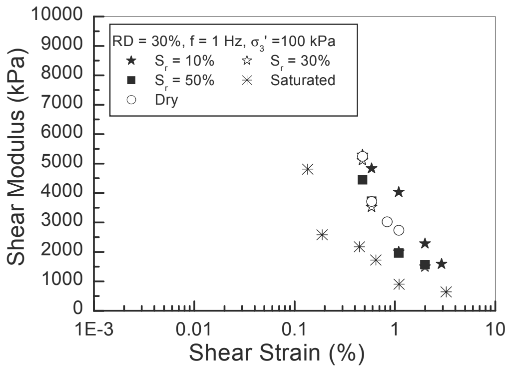

Figure 5. Shear modulus of Ahmedabad sand at different degrees of saturation and shear strain (Sitharam et al.)

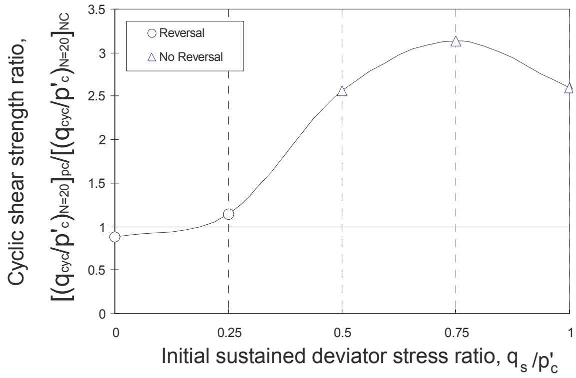

Figure 6. Ratio of cyclic shear strength from the second cyclic loading to that from the first cyclic loading versus the initial sustained deviator stress ratio (Hyde and Higuchi)

2.2 *Repeated and irregular cyclic loading*

Hyde and Higuchi investigated the "Post-liquefaction characteristics of low plasticity silt" using cyclic triaxial testing of a powdered limestone. Specimens were anisotropically consolidated at different initial deviator stress ratios (q_s/p_c'), and then subjected to undrained cyclic loading to failure (strains of about 5%). After this first stage of cyclic loading, the specimens were allowed to reconsolidate before being subjected to a second stage of undrained cyclic loading. Samples with a greater initial q_s/p_c' ratio had less volumetric strain but larger axial strains during reconsolidation after the first stage of cyclic loading. The cyclic strength for the second stage of loading was slightly reduced relative to the first stage of loading for specimens with an initial q_s/p_c'=0, but was almost tripled for specimens with an initial $q_s/p_c'=0.75$ (Fig. 6). These results provide insight into the role of consolidation stress ratio and shear stress reversal on the evolution of soil fabric and subsequent cyclic loading behavior.

Teymur and Madabhushi studied the "Liquefaction potential of horizontal layers in successive earthquakes" by performing a series of dynamic centrifuge model tests on clean sand placed at different initial relative densities. Miniature cone penetration tests were performed before and after each shaking event. The results showed that the loose saturated sand profiles could be repetitively liquefied by shaking, although the sand did show a progressive increase in liquefaction resistance as it became progressively denser and its cone penetration resistance increased following each shaking event (Fig. 7).

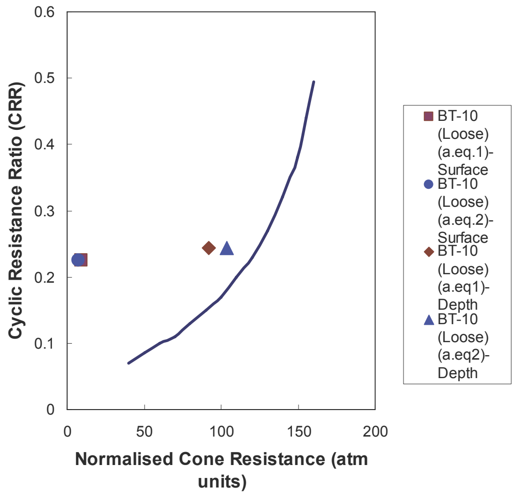

Figure 7. Cyclic stress ratio versus cone penetration resistance for clean sand liquefied by successive shaking events in centrifuge tests (Teymur and Madabhushi)

Kim, Park, Park, Hwang, Lee, and Choi described the "Effects of irregular dynamic loads on soil liquefaction," in which they performed undrained triaxial tests with axial loading time series that were sinusoidal, triangular, incrementally-increasing, and earthquake wave forms. They introduced a stress damage ratio as a means of describing various dynamic loadings, and discuss their results in terms of cumulative energy dissipation. Their results reinforce existing literature in showing the differences between the undrained responses of sand during uniform cyclic versus earthquake waveform loading.

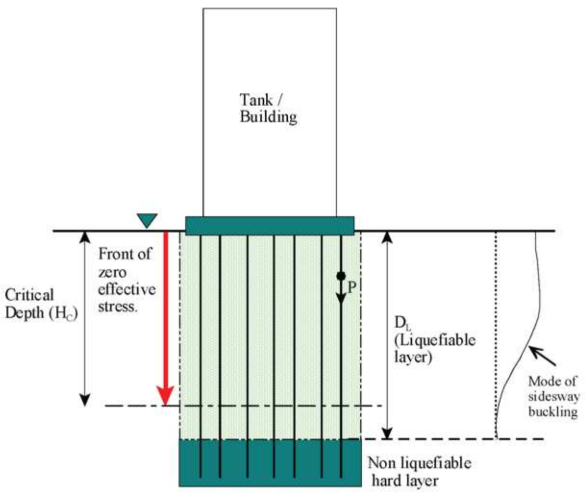

Figure 8. Schematic showing concept of critical depth for the mode of side-sway buckling of piles in liquefied soil (Bhattacharya et al)

2.3 *Foundations*

Bhattacharya, Bhattacharya, and Madabhushi describe "Risk evaluation of existing piled foundations in liquefiable soils." The authors consider the possibility of pile buckling under axial loads with the loss of lateral support in the liquefied layers (Fig. 8). A risk analysis for pile buckling was illustrated for a case history from Kobe. The pile diameter was identified as the factor having the greatest influence on the computed risk of buckling. The authors' results bring attention to the importance of geometric or P-Δ effects on the response of piles in areas of liquefaction and lateral spreading.

Haigh, Coelho, and Madabhushi analyzed centrifuge tests of shallow bridge foundations on liquefying sand in their study "On the prediction of dynamic behavior using numerical and physical modeling." Coupled finite element analyses using a generalized plasticity bounding surface model were first performed for a centrifuge model involving a level soil profile of saturated sand. The constitutive parameters were calibrated to obtain reasonable agreement with the recorded responses of this centrifuge model. The calibrated constitutive parameters were then used in predictive analyses of centrifuge models that involved bridge piers supported on shallow footings over saturated sand. The calculated and recorded responses were in reasonable agreement (Fig. 9), illustrating the utility of the calibrated finite element models for assessing the effects of physical variations from the baseline (calibration) conditions.

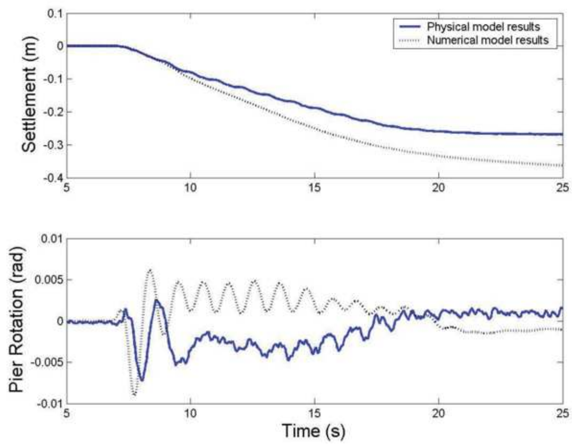

Figure 9. Measured and computed settlements and rotations for a bridge pier over liquefying sand in dynamic centrifuge model test (Haigh et al.)

Kano, Sasaki, and Hata evaluate the "Effects of three dimensional response of dikes on their local failures during an earthquake." Seismic damage is often limited to localize zones along a dike despite the fact that the foundation conditions do not appear to have significantly varied along the dike. Shaking table tests were performed of long model embankments (480 mm long, 40mm tall) over a 20-mm to 80-mm thick foundation layer. The embankment and foundation were modeled using gelatin. The model was shaking with sinusoidal motion at frequencies varying from 3 Hz to 35 Hz. The dynamic response of the embankment included a harmonic wave-like displacement distribution (mode shape) along the embankment axis. Comparing points along the dike that would correspond to either a node or anti-node for this mode of response, it was shown that the dynamic displacements would be stronger at the anti-node location. Expressions were derived that describe the length of this wave along the embankment axis based on the model's geometry and stiffness properties. The wavelength for this mode of response was computed using properties representative of the soft foundation conditions along the Kushiro River, and shown to be on the order of 300 m (prototype). The Kushiro River dike developed periodic failures along its length during the 1993 Kushiro-

Figure 10. Aerial photograph of Kushiro River dike showing failed sections at periodic intervals (Kano et al.)

Oki earthquake, with failed sections being about 120 to 230 m long and the distances between failed sections being about 260 to 340 m long (Fig. 10). The pattern of damage is therefore consistent with the authors' model for this additional three-dimensional mode of dynamic response.

2.4 *Field Studies and Testing of Field Samples*

Monaco, Marchetti, Totani, and Calabrese formulate a new tentative correlation for "Sand liquefiability assessment by Flat Dilatometer Test (DMT)." The basis for correlating liquefaction resistance to the DMT's horizontal stress index K_D was reviewed, including the sensitivity of K_D to pre-straining and relative density, and its correlation to the state parameter. The new CRR-K_D correlation (Fig. 11) was developed from CPT and SPT based liquefaction correlations by mapping CPT and SPT penetration resistances to equivalent K_D values (using D_R as an intermediate parameter in the mapping). Future advances in our ability to predict liquefaction triggering and consequences will benefit from these, and related efforts, to relate the results of in situ test measurements to fundamental soil characteristics, and may in fact benefit from characterization efforts that utilize a combination of in situ test results.

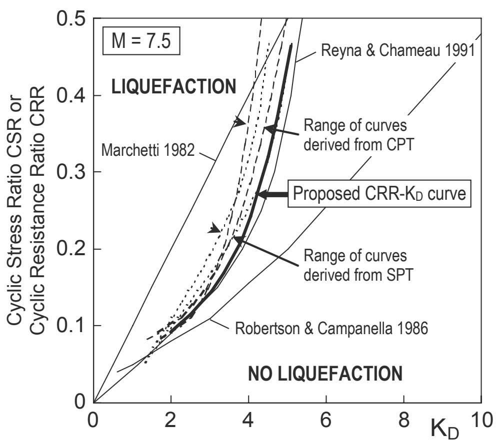

Figure 11. CRR-K_D curves for estimating liquefaction resistance from DMT (Monaco et al.)

Fujiwara, Horikoshi, and Sakai present the "Development of a sampler designed for laminar box and its application to dynamic centrifuge modeling of footing settlement due to liquefaction." The new sampler was used to obtain relatively large undisturbed samples (400 mm diameter, 500 mm height) of very dense silty sand (relative density 128%; 16% fines) that were later transferred to a circular laminar box for dynamic testing in a centrifuge. A model footing was embedded in the soil sample before testing (Fig. 12). The model was shaken with 20 uniform cycles of sinusoidal acceleration having peak amplitude of 0.36 g (prototype). Tests were also performed with the soil reconstituted to a similar relative density. The settlement of the ground surface and footing for the test using an undisturbed soil sample were about 10% and 20% less, respectively, than the corresponding values for the test with reconstituted soil. The differences in response were attributed to factors such as aging and cementation. The authors' efforts to perform centrifuge tests on high-quality field samples has attractive benefits given the breadth of literature demonstrating the importance of age, cementation, fabric, and prior stress-strain history on the cyclic behavior of sands. The literature also includes numerous examples showing that very dense sands are particularly sensitive to the effects of sampling disturbance (e.g., Yoshimi et al. 1994), which is an aspect that the authors can address as they acquire experience with their new sampling and testing procedures.

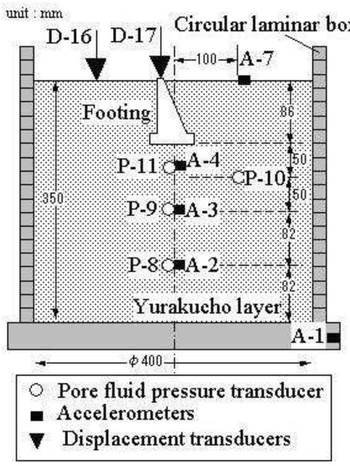

Figure 12. Centrifuge model arrangement for study using large undisturbed soil samples (Fujiwara et al.)

Stamatopoulos and Aneroussis present a "Back analysis of liquefaction failure and relationship between the residual soil strength and the N value of the SPT." The authors use a multiple block model to analyze the kinematics of slide mass movements during earthquake shaking. Results are presented for one case history, and then combined with results from seven other case histories to produce a correlation between residual strength (S_r) and SPT $(N_1)_{60}$ values. The final correlation suggests S_r increases with $(N_1)_{60}$ and decreases with increasing fines content.

Luna and Jadi describe "Effective stress back-analysis of past earthquake ground motions at paleoliquefaction sites." The authors use a one-dimensional, nonlinear, effective stress-based, site response program to determine earthquake ground motions and associated seismic parameters (magnitude, distance, and peak ground acceleration) that are consistent with the past occurrence of liquefaction at a paleoliquefaction site. The authors acknowledge the limitations of the methodology, and list the in situ penetration resistance and dynamic soil properties (and how they may have varied between the time of the paleoliquefaction event and their measurement in present times) as having the greatest effect on the final results, as expected.

2.5 *Remediation*

Yamazaki, Hayashi, and Zen describe a "New liquefaction countermeasure based on pore water replacement," whereby a permeable grouting method (PGM) was used to inject a silica gel substance in sands. The grouting method increased the grout travel distances such that grout holes could be spaced at two to four meter intervals (e.g., Fig. 13). The chemical concentration of the injected grout was varied with time to compensate for the effects of dispersion and dilution with ground water, thereby improving the uniformity of the treated soil versus distance from injection points. Since its introduction in 1999, the PGM has been applied to forty projects.

Figure 13. Photograph of soil improved by permeable grouting method, as exposed in an excavation at a field test site (Yamazaki et al.)

Coelho, Haigh, and Madabhushi described the "Development, effects and mitigation of earthquake-induced liquefaction: a comprehensive study based on dynamic centrifuge modelling." Their study included eight centrifuge model tests for bridge decks supported on shallow foundations (4m by 8 m in plan; prototype dimensions) over 18 m of saturated sand, subjected to sinusoidal horizontal base shaking. The supporting sand was loose (relative density of D_R=50%) except for "improved" zones (placed at D_R=80%) of different extent beneath the bridge footing. The total earthquake-induced footing settlement (for one model geometry) was about 790 mm (prototype) without an improved zone and between 250 mm and 300 mm with improved zones having widths equal to 1 to 3 times the footing width. Thus the results showed significant benefits from having an improved zone, but relatively small benefits from increasing the width of the improved zone to values much greater than the footing width. Centrifuge tests with level ground showed relative small differences in the rate of pore pressure generation for loose versus dense sand; The authors note that this appears inconsistent with expectations from laboratory elements test data, and suggest it may be due to the effects of pore water seepage in the physical models. The presence of an improved zone was also noted to cause a stronger dynamic response of the superstructure, which increased the inertial loads that the footing had to resist.

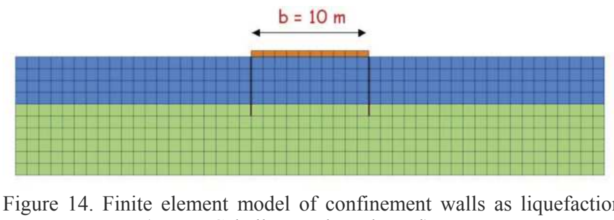

Figure 14. Finite element model of confinement walls as liquefaction countermeasure (Lopez-Caballero and Modaressi)

Lopez-Caballero and Modaressi present a study on "Numerical modeling of confinement walls as liquefaction countermeasure." Two-dimensional coupled finite element analyses were used to evaluate the efficiency of in situ confinement walls as a means to mitigate liquefaction effects (Fig. 14). The role of the confinement wall's rigidity and permeability were numerically illustrated. It would be interesting to see the authors evaluate their 2D numerical models for confinement walls against results from dynamic centrifuge model tests (e.g., Babasaki et al. 1991).

3 SITE EFFECTS, ZONATION, AND FAULT RUPTURE

Sunuwar, Karkee, Pokharel, and Lohani present a "Comparative study of seismic hazard of Kathmandu valley, Nepal with other seismic prone cities." The study used historical earthquake records for a 400 km radius to establish a recurrence relation and a recently developed attenuation relation for crustal earthquakes in Taiwan to estimate peak ground accelerations. A hazard curve for peak ground acceleration on rock was subsequently developed and compared to hazard curves that were produced by others for Los Angeles (USA) and Sendai (Japan). The likely importance of site effects in the Kathmandu valley, with its abundant soft lacustrine soils, was discussed. The authors noted that the reluctance of the authorities to strictly implement earthquake resistant design codes contributes to the continuing high vulnerability of infrastructures in the Kathmandu valley.

Rao and Satyam describe "Site characterization through microtremor studies for seismic microzonation of Delhi." Microtremors were recorded at thirty one locations, from which the locations were grouped into five categories based on their H/V ratios. The five categories corresponded to soil profiles that ranged from loose sandy silt and silty sand (Holocene alluvium) to weathered quartzite.

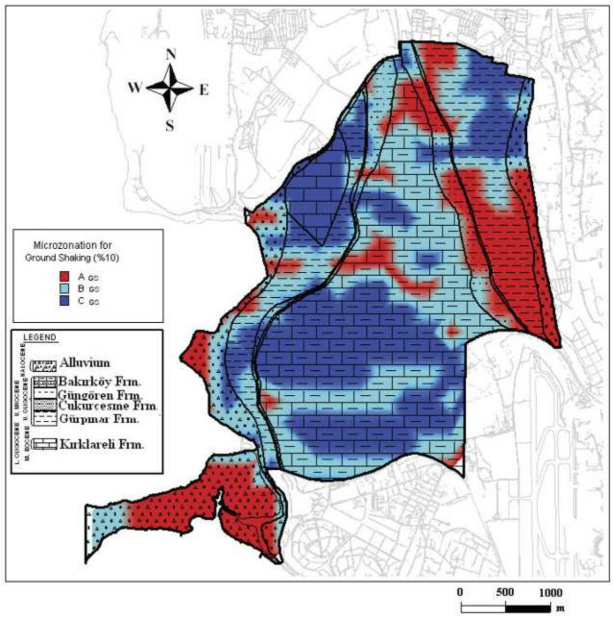

Figure 15. Seismic zonation map for ground shaking overlain on geologic map for Kucukcekmece region (Kilic et al.)

Kilic, Ozener, Yildirim, Ozaydin, and Adatepe present an "Evaluation of Kucukcekmece region with respect to soil amplification" for microzonation purposes following the procedures recommended in the Microzonation Manual prepared by the World Institute for Disaster Risk Management. Earthquake acceleration time histories were developed that are compatible with the uniform hazard response spectra corresponding to a 10% probability of exceedance in 50 years. One-dimensional equivalent-linear site response analyses were then performed using the results of soil exploration borings, geophysical surveys, and microtremor measurements that defined the geological characteristics of the region. GIS mapping procedures were then used to produce the final zonation maps (e.g., Fig. 15).

Lanmin, Zhijian, Dongli, and Luxin discuss "The influence of earth temperature on dynamic characteristics of frozen soil and the parameters of ground motion at the sites of permafrost in the Qinghai-Tibet plateau." The authors show how varying the temperature from -2°C to -10°C can have significant effect on the dynamic strength of frozen soils (perhaps a factor of 3; Fig. 16). Seismic site response analyses were performed for four different sites for a range of ground temperatures, and the results illustrated the computed effects on site period, peak ground acceleration, peak ground velocity, and peak ground displacement.

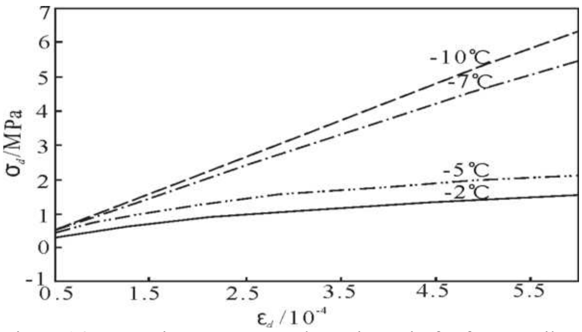

Figure 16. Dynamic stress versus dynamic strain for frozen soils at different temperatures (Lanmin et al.)

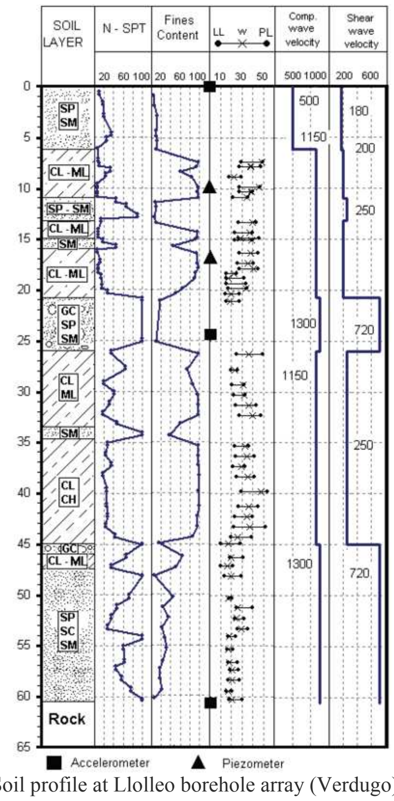

Figure 17. Soil profile at Llolleo borehole array (Verdugo)

Verdugo describes the "Influence of the surface layers on the site effect" based on observations from record ground motions at a downhole seismic array in Chile. The downhole array has accelerometers at the surface and at depths of 24 m and 62 m (just into the bedrock). The soil profile includes inter-layered sand and silty clay strata with shear wave velocities varying from 180 to 720 m/s (Fig. 17). Ground motion records suggest that the majority of the amplification in the recorded ground motions occurred in the upper 20 to 30 m. Some ground motion recordings showed considerable differences in the amplification of peak horizontal accelerations in the two orthogonal directions; Understanding the sources of these differences (e.g., two dimensional basin effects or different frequency contents in the bedrock motions for the two orthogonal directions) will require site response analyses.

Anastasopoulos presents a study on "Behavior of foundations over surface fault rupture: Analysis of case histories from the Izmit (1999) earthquake." Three buildings located along the fault where vertical offsets of 1.5 to 2.3 m occurred, are analyzed: Building 1 having 0.3-m wide by 0.6-m high strip footings transversely connected by tie beams of similar dimensions, Building 2 having cinder block walls that were practically founded directly on the soil without any foundation, and Building 3 having a relatively rigid box-type foundation. The fault rupture was aligned to intersect the corners of Buildings 1 and 3, but the ruptures were locally diverted enough to miss the buildings. In contrast, the fault rupture tore apart Building 2, with its weak foundation. Analyses of fault rupture propagation in a 40-m-thick soil profile were performed using two-dimensional plane-strain finite element analyses with an elastoplastic constitutive model. The analyses were repeated with and without a building foundation present, and the results illustrated how a relatively strong building foundation can improve the building performance and even cause the fault rupture to locally divert away from the path it would have taken if the building had not been there (e.g., Fig. 18).

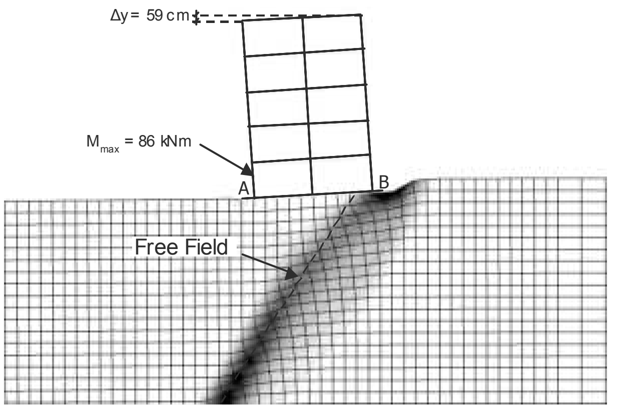

Figure 18. Finite element model of fault rupture propagation beneath Building 1 (Anastasopoulos)

4 SLOPE STABILITY AND EARTH PRESSURES

Loukidis, Bandini, and Salgado describe the solution of "Critical seismic coefficient using limit analysis and finite elements" for simple two-dimensional slopes. The critical seismic coefficient (k_c) is the pseudo-static horizontal acceleration that just produces yielding of the slope (factor of safety of 1.0). The k_c values and critical slip surfaces from the numerical limit analyses (with rigorous lower and upper bounds), finite element analyses, and limit equilibrium methods were all in reasonable agreement for soil that follows an associative flow rule (Fig. 19). A limited number of finite element analyses with a non-associative flow rule showed that the modeling of soil dilatancy did affect the value of k_c, and that limit analysis and limit equilibrium solutions may be slightly unconservative.

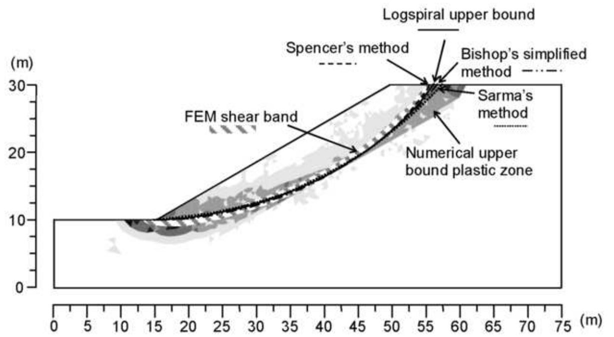

Figure 19. Comparison of critical slip surfaces obtained from limit equilibrium methods and plasticity zones determined from numerical upper bound analyses and the finite element method (Loukidis et al.)

Ortigosa described the development of a theory for predicting "Seismic earth pressure including soil cohesion." The author uses continually varying combinations of c and ϕ to describe a soil's strength envelope at different levels of induced shear strain. The seismic earth pressure was computed based on these different c-ϕ combinations and a planar failure mechanism (as by Mononobe-Okabe for sand). Shear strains induced in the backfill were related to the normalized wall displacements. Examples were presented for how the computed static and seismic thrusts can therefore be expected to vary with normalized wall displacements.

5 DISCUSSION

The papers in this session cover many interesting earthquake-related problems that are worthy of more detailed discussion, but which are beyond the scope of this general report. Consequently, this discussion is limited to a couple of general issues relevant to liquefaction problems, since they were clearly a major focus of the papers in this session.

Discussion of liquefaction problems often benefits from a clarification of the technical meaning that individuals may be assigning to the term "liquefaction." For example, it is not uncommon for an individual to assume that liquefaction is defined by either an excess pore water pressure ratio (r_u) of 100%, a shear strain of some specified magnitude (e.g., 7.5%), flow deformations under an imposed shear stress, or the occurrence of sand boils and ground deformations in the field. These definitions are not mutually inclusive, as illustrated by the facts that flow deformations can develop without r_u ever reaching 100% and that the temporary development of r_u=100% during cyclic loading does not necessarily result in flow deformations (e.g., see the many examples in Ishihara 1996). The situation is further complicated in the field, where the observation of sand boils and ground deformations is indicative of high excess pore water pressures and significant shear strains in the soil, but the exact determination of their magnitudes is uncertain. For example, some of the studies in this session illustrate how the presence of an initial static shear stress (such as exist within slopes or beneath loaded footings) may preclude the development of r_u=100% without precluding the development of significant shear strains (with associated ground deformations or foundation settlements). In this regard, it may be preferable to accept that "liquefaction" can be used in reference to a broad range of phenomena that are associated with the development of significant excess pore water pressures and shear strains in saturated cohesionless soils during cyclic loading, and then provide explicit definitions for any failure criteria that are being used to describe or evaluate the results of laboratory or physical model tests.

Sampling disturbance and the differences in behavior between in situ soils and reconstituted specimens continue to be challenging problems. The importance of age, cementation, fabric, and prior stress-strain history on the cyclic behavior of sands is well established in the literature (e.g., Finn et al. 1970, Mulilis et al. 1977, Ishihara et al. 1977, Seed 1979, Ishihara and Takatsu 1979, Suzuki and Toki 1984, Tatsuoka et al. 1988, Yoshimi et al. 1994). The papers in this session include several good examples of research efforts that either directly investigated these phenomena or considered the impact that these phenomena could have had on their findings. A question that arises from those lessons is the extent to which laboratory element tests or physical models using freshly reconstituted, homogenous, laboratory specimens are directly applicable to heterogeneous field deposits having significant age or stress-strain history (including the effects of construction processes). Adopting experiences from one situation to another, whether from a physical model to the field, or from one field site to another, requires a clear understanding of the physical mechanisms involved and an assessment of how the differences in conditions might affect the resulting behavior. For example, the phenomena of void redistribution or water film formation (e.g., see Malvick et al. in another session) is strongly dependent on stratigraphy, and its potential influence on field behavior is not captured in either laboratory element tests or physical models with homogenous soil profiles. Recognizing these various factors and explicitly considering their importance to field performance are essential components of geotechnical earthquake engineering research and practice.

The papers in this session illustrate the broad range of tools and approaches available for the study of liquefaction problems, including theoretical developments, laboratory element testing, physical modeling, numerical modeling, site characterization, seismic hazard characterization, construction techniques, and zonation. Each of these tools or approaches provide a unique insight or capability that can be invaluable in overcoming fundamental and practical problems, but each tool or approach also has inherent limitations that can restrict its general applicability or accuracy in certain situations. The challenge is the effective integration or synthesis of information from across the range of tools or approaches at our disposal, with due recognition for when individual sources of information may be potentially misleading on their own.

6 CONCLUSION

The twenty eight papers of this session illustrate a broad range of research endeavors related to earthquake engineering problems. There are examples of research involving theoretical developments, laboratory element testing, physical modeling, numerical modeling, site characterization, seismic hazard characterization, construction techniques, and zonation. This range of activities portends well for future advances, wherein the synthesis of insights provided by these activities, with due recognition for the inherent limitations in each of our available tools, provides the best opportunity for developing improved methods for assessing and mitigating seismic hazards.

REFERENCES

Babasaki, R., Suzuki, K., Saitoh, S., Suzuki, Y., and Tokitoh, K. (1991). "Construction and testing of deep foundation improvement using the deep cement mixing method." Deep Foundation Improvements: Design, Construction, and Testing, ASTM STP 1089, Esrig and Bachus, Eds.

Boulanger, R. W., and Idriss, I. M. (2004). "Evaluating the potential for liquefaction or cyclic failure of silts and clays." Report No. UCD/CGM-04/01, Center for Geotechnical Modeling, Dept. of Civil & Environmental Engrg., Univ. of California, Davis, 129 pp. http://cgm.engineering.ucdavis.edu/Publications/reports.htm.

Finn, W. D. L., Bransby, P. L., Pickering, D. J. (1970). "Effect of strain history on liquefaction of sand." Journal of the Soil Mechanics and Foundations Division, ASCE, 96(SM6), 1917-1934.

Ishihara, K. (1996). Soil Behavior in Earthquake Geotechnics, Oxford engineering science series 46, Oxford University Press Inc., New York.
Ishihara, K., and Takatsu, H. (1979). "Effects of overconsolidation and K_o conditions on the liquefaction characteristics of sands." Soils and Foundations, JSSMFE, 19(4), 59-68.
Ishihara, K., Iwamoto, S., Yasuda, S., and Takatsu, H. (1977). "Liquefaction of anisotropically consolidated sand." Proc., Ninth Int. Conf. on Soil Mechanics and Foundation Engineering, JSSMFE, Tokyo, Japan, Vol. 2, 261-264.
Mulilis, J. P., Seed, H. B., Chan, C. K., Mitchell, J. K., and Arulanandan, K. (1977). "Effect of sample preparation on sand liquefaction.”"Journal of the Geotechnical Engineering Division, ASCE, 103(GT2), 91-108.
Seed, H. B., (1979). "Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes." J. Geotechnical Engineering Division, ASCE, 105(GT2), 201-255.
Suzuki, T., and Toki, S. (1984). "Effects of preshearing on liquefaction characteristics of saturated sand subjected to cyclic loading." Soils and Foundations, JSSMFE, 24(2), 16-28.
Tatsuoka, F., Kato, H., Kimura, M., and Pradhan, Tej B. S. (1988). "Liquefaction strength of sands subjected to sustained pressure.”"Soils and Foundations, JSSMFE, 28(1), 119-131.
Yoshimi, Y., Tokimatsu, K., and Ohara, J. (1994). "In situ liquefaction resistance of clean sands over a wide density range." Geotechnique, 44(3), 479-494.

PAPERS IN TECHNICAL SESSION 4B

Anastasopoulos, I. (2005). "Behaviour of foundations over surface fault rupture: Analysis of case histories from the Izmit (1999) Earthquake."
Bhattacharya, G., Bhattacharya, S., Madabhushi, G. (2005). "Risk evaluation of existing piled foundation in liquefiable soils."
Brenner, R.P., Wieland, M., Malla, S. (2005). "Large-diameter cyclic triaxial tests for seismic safety assessment of an earth dam."
Coelho, P.A.L.F., Haigh, S.K, Madabhushi, S.P.G. (2005). "Development, effects and mitigation of earthquake-induced liquefaction: a comprehensive study based on dynamic centrifuge modeling."
Fleureau, J.-M., Hadiwardoyo, S., Kheirbek-Saoud, S. (2005). "Seismic sensibility of a dam material."
Fujiwara, T., Horikoshi, K., Sakai, K. (2005). "Development of a sampler designed for laminar box and its application to dynamic centrifuge modeling of footing settlement due to liquefaction."
Haigh, S., Coelho, P., Madabhushi, G. (2005). "On the prediction of dynamic behaviour using numerical and physical modeling."
Huang, A.B., Huang, Y.T., Ho, F.J. (2005). "Assessment of liquefaction potential for a silty sand in Central Western Taiwan."
Hyde, A.F.L., Higuchi, T. (2005). "Post liquefaction characteristics of low plasticity silt."
Kano, S., Sasaki, Y., Hata, Y. (2005). "Effects of three dimensional response of dikes on their local failures during an earthquake."
Kılıç, H., Tohumcu Özener, P., Yıldırım, M., Özaydın, K., Adatepe, Ş. (2005). "Evaluation of Küçükçekmece region with respect to soil amplification."
Kim, S.I., Park, K.B., Park, S.Y., Hwang, S.J., Lee, J.H., Choi, J.S. (2005). "Effects of irregular dynamic loads on soil liquefaction."
Laue, J., Buchheister, J. (2005). "Load path and loading velocity as potential condition indicator for liquefaction of silty soils."
Lopez-Caballero, F., Modaressi, A. (2005). "Numerical modeling of confinement walls as liquefaction countermeasure."
Loukidis, D., Bandini, P., Salgado, R. (2005). "Critical seismic coefficient using limit analysis and finite elements.
Luna, R., Jadi, H. (2005). "Effective stress back-analysis of past earthquake ground motions at Paleoliquefaction Sites."
Monaco, P., Marchetti, S., Totani, G., Calabrese, M. (2005). "Sand liquefiability assessment by Flat Dilatometer Test (DMT)."
Ortigosa, P. (2005). "Seismic earth pressure including soil cohesion."
Rao, K.S., Neelima Satyam, D. (2005). "Site characterization through microtremor studies for seismic microzonation of Delhi."
Sitharam. T.G., Ravishankar, B.V., Govinda Raju, L. (2005). "Deformation characteristics of sandy soils subjected to cyclic loads."
Stamatopoulos, C., Aneroussis, S. (2005). "Back analysis of liquefaction failure and relationship between the residual soil strength and the N value of the SPT."
Sunuwar, L., Karkee, M.B., Pokharel, G., Lohani, T.N. (2005). "Comparative study of seismic hazard of Kathmandu valley, Nepal with other seismic prone cities."
Teymur, B., Madabhushi, S.P.G. (2005). "Liquefaction potential of horizontal layers with successive earthquakes."
Van Laak, P.A., Ng, C.W.W. (2005). "Stability of loose CDG fill slopes subjected to uni-axial and bi-axial earthquakes in a centrifuge."
Verdugo, R. (2005). "Influence of the surface layers on site effect."
Wang, L., Wu, Z., Zhang, D., Zhang, L. (2005). "The influence of earth temperature on dynamic characteristics of frozen soil and the parameters of ground motion at the sites of permafrost on the Qinghai-Tibetian Plateau."
Yamashita, S., Ito, Y., Hori, T., Suzuki, T., Murata, Y. (2005). "Geotechnical properties of liquefied volcanic soil ground by 2003 Tokachi-Oki Earthquake."
Yamazaki, H., Hayashi, K., Zen, K. (2005). "New liquefaction countermeasure based on pore water replacement."