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General Report— Session 1: Dynamic Properties for Soils Engineering Soil Parameters and Constitutive Relations: New Field and Laboratory Results

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DYNAMIC PROPERTIES FOR SOILS ENGINEERING SOIL PARAMETERS AND CONSTITUTIVE RELATIONS: NEW FIELD AND LABORATORY RESULTS

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General Report – Session I

INTRODUCTION

A total of forty-four papers were received for this session. A similar session at the last conference held in St. Louis in April 1995 had twenty-seven papers. This reflects a continuously growing interest in the research into constitutive modeling soil parameters, and their measurement. Such research is vital for a complete understanding of a host of seismic problems including site response to ground motion, liquefaction, and soil structure interaction. The papers have been received from various parts of the world and are very interesting.

The papers can be broadly classified into three categories: small strain phenomena with emphasis on site response, large strain phenomena or plastic yielding dealing with liquefaction, and elastic-plastic phenomena. Most of the papers focused on the small strain phenomena (about 60 percent), while about 30 percent dealt with plastic yielding and the remaining 10 percent encompassed both elastic and plastic phenomena. It is understood, however, that some of the papers discussed under one category may easily fall into other categories.

Small strain phenomena: (25 papers) (60%)
- stiffness and damping
- soil-structure interface characteristics

Large strain phenomena- Plastic yielding: (14 papers) (30%)
- monotonic shear strength-deformation behavior
- cyclic shear strength characteristics
- dynamic analysis
- liquefaction and post-liquefaction behavior

Elastic and plastic yielding phenomena: (5 papers) (10%)
- elasto-plastic behavior of soils
- deformation analysis

SMALL STRAIN PHENOMENA

Paper #1.05 by Yu et al. described an effective stress-based seismic response analysis, consisting of four major formulations for calculating the shear modulus, the damping ratio, the excess pore water pressure and the subsidence of horizontal soil layers. It was applied to 280m-deep soil layers in Shanghai, and a reduction of the peak accelerations from 0.10g at the bedrock to 0.09g at the ground surface was reported as well as a change in their frequency components.

Paper #1.07 by Arulnathan et al. presents an overview of recent research on the site response characteristics of organic soils using centrifuge and numerical modeling. The centrifuge tests were performed on a profile consisting of a peat layer placed in between two dense sand layers. The thickness of the different layers was modified to control the range of consolidation stresses on the peat and the fundamental period of the entire soil profile. The models were subjected to a series of earthquake ground motions of progressively larger intensities. Pore pressures were allowed to dissipate in between events. Shear wave velocity measurements were obtained during centrifuge testing using a device developed by the authors. The measured shear wave velocities are in agreement with measurements in laboratory triaxial tests using piezo-ceramic bender element methods. The measured shear wave velocity profile along with modulus reduction and damping curves previously published by Boulanger et al. (1998) were used in one-dimensional, equivalent-linear site response analyses. The results of the analyses match well with the recorded centrifuge model acceleration time histories. These tests provide an invaluable addition to the small database of published studies on the dynamic behavior of organic soils.

Paper #1.08 by Modaressi and López-Caballero presents a methodology to identify model parameters needed for an elastoplastic model used in the one-dimensional site response program CyberQuake. Soils are identified by means of their shear modulus reduction and equivalent viscous damping versus strain curves (G-λ and D-λ curves). Key model parameters are correlated to easily measurable physical parameters, such as the Atterberg limits for clays, and the relative density and the C_u ratio for sands. In addition to those parameters that are obtained from correlations, a set of parameters is determined by matching the response of the model in shear to published G-λ and D-λ curves. The methodology is straightforward and makes use of an extensive number of published correlations. The G-λ and D-λ curves predicted by the model for Hostun RF sand reproduce remarkable well the measured curves. On the other hand, for a PI=30 clay the model matches well the shear modulus reduction curve, but overestimates damping at low strains, and significantly underestimates damping at large strains. An example is presented on a one-dimensional site response analysis of Mexico city clay using the indicated nonlinear model. Results show an improvement over the more traditional equivalent linear method.

Paper #1.13 by Cavallaro et al. describes a laboratory study to obtain geotechnical characterization of dry reconstituted specimens of uncemented sand. Based on results from direct shear tests an empirical correlation was proposed between shear resistance angle and relative density. The physical state of a specimen is reflected by dilatancy and therefore the above correlation must include this parameter to have wider application. This state must be expressed in terms of relative density in conjunction with stress level.

The resonant column (RCT)/torsion shear (TST) apparatus was also used to study the variation of shear modulus (G) and damping ratio (D) with shear strain level from less than 0.001% to 0.5%. For the very small strain range (< 0.001%) the elastic shear modulus obtained with RCT or the cyclic TST is identical for the same physical state of the specimen, corroborating previous findings of no significant influence of frequency. However, D values obtained by RCT are generally greater than those obtained by cyclic TST, which is also consistent with findings showing the effect of frequency/strain rate in this parameter. However, the authors didn't refer about the number of cycles, which may have a major influence with increase of strain level.

Results were also used to infer parameters for well-established empirical correlations to predict the very small strain shear modulus, to describe shear modulus degradation curves and to establish the inverse variation of damping ratio with respect to the normalized shear modulus.

Paper #1.14 by Foti et al. proposed a multi-station approach for the SASW (spectral analysis of surface waves) method. Its advantages include improvement of robustness and stability, clearer signal interpretation, reduction in the testing time, and a possibility of automating the process of estimation of the experimental dispersion curve. Some results from a two-receiver procedure were presented, and the shear wave profile obtained showed a good agreement with those of a cross-hole test.

Paper #1.17 by Abrahamyan used instrumental observations made during the 1988 Armenian earthquake to find a connection between large-scale destruction and some dynamic peculiarities of grounds. No concrete conclusions, however, were reached in the analysis.

Paper #1.19 by d'Onofrio and Silvestri presents a compilation of test data from the literature on small strain shear stiffness and small strain damping. The test data are fitted to a power law relationship between normalized small strain stiffness and damping and mean confining pressure. The coefficients of the power law relationships are then correlated to plasticity index. The data show that stiffness decreases with increasing plasticity, while small strain damping increases with increasing plasticity. The data also show that soils deposited in a fluvial environment have larger stiffness and damping ratio than those deposited in a marine environment. This is presumably due to differences in the microstructure. Finally, the authors use the developed correlations along with the shear modulus reduction and damping versus strain curves of Vucetic and Dobry (1991) to perform a sensitivity analysis of the influence of plasticity index on site response. Conclusions presented by the authors rely on extrapolation of the test data from plasticity indices lower than 60 to large plasticity indices ($I_p > 100$). This results in excessively large small strain damping ratios. Moreover, the choice of plasticity index as an estimator of soil microstructure is not fully justified. No information on void ratio (a more direct measure of microstructure) for the tests is presented.

Paper #1.21 by Park and Stewart made a regression analysis of existing experimental data on the relationship between the normalized shear modulus G/G_{max} and the damping ratio D. Empirical equations were obtained with coefficients of determination (r^2) of 0.918 and 0.844, respectively, for sandy soils and clayey soils. The damping ratio of clayey soils was smaller than that of sandy soils in most cases, while their minimum-damping ratio was larger than that of sandy soils.

Paper #1.22 by Correia et al. presented results from resonant column tests on a wide variety of lateritic and saprolitic tropical soils. The strain dependence of shear modulus in the strain range of 10^{-6} to 10^{-2} could be modeled by a hyperbolic equation in terms of normalized parameters G/G_o and $\gamma/\gamma_{0.7}$, where $\gamma_{0.7}$ is the shear strain at $G=0.7*G_o$. An empirical relationship to estimate the small strain shear modulus G_o from SPT-N value was also proposed for these tropical soils, which was significantly different from the ones previously proposed for ordinary soils.

Paper #1.24 by Zhang and Aggour conducted a series of tests to determine the Young's modulus of sands under various types of dynamic compression loading using the resonant column device. Specimens were tested with sinusoidal, random, or impulse excitation. An empirical equation that determines Young's modulus as a function of the axial strain amplitude was developed for the different types of loading, and good agreement between the computed values of Young's modulus of sand specimens were achieved with each equation. Under the three types of loading, the Young's modulus decreased with an increase of axial strain.

Paper #1.28 by Sincraian et al. reports on the influence of lateral faults in the nonlinear dynamic effects of an alluvionar valley. The study employed the discrete element code UDEC for the analysis. A bi-dimensional cross section of the valley was considered along with a Mohr-Coulomb model. Based on this preliminary study it has been found that around the fault and near the surface, the seismic response in terms of the maximum values of shear strain has higher values than in other parts of the cross section. Further studies are necessary to get a better understanding of the soil in the region of the valley.

Paper #1.30 by Fleureau et al. presents a study on the influence of compaction water content, aging, and different test apparatus on measured shear modulus of silty sand. Tests were conducted using resonant column as well as triaxial cell using Hall effect-based local strain gauges. They found that molding water content had no influence on shear modulus in the strain range of 10^{-6} to 10^{-4} %. Aging did have a notable influence. Similar results were observed regardless of differences in the modes of loading in the two apparatuses.

Paper #1.31 by Tzyy-Shiou et al. presents evaluations of trial improvements of static and dynamic properties of layers of soft clay located at the site of a proposed subway. The properties were improved using a high-pressure jet grout. The ideas presented would be expected to apply to, for example, soil improvements for earthquake engineering purposes. Trial grout columns were formed at the site. Then, to evaluate the impact of the grouting, samples were recovered from the natural soil and the grouted areas and tested both statically and dynamically using laboratory triaxial and resonant column testing equipment. The authors report significant changes in unconfined compression strengths, low strain shear wave velocities/shear moduli, low strain damping ratios, and normalized shear modulus reduction vs shear strain curves. Impacts on these characteristics of confining pressure (depth), and the cement content and the water/cement ratio of the grout were established. Notable conclusions include 1) that the effects of grouting appear to be more pronounced at lower confining pressures (shallower depths), 2) that grouting greatly increases low strain damping ratios, and 3) that grouting increases the strain range over which elastic behavior occurs. The effective lateral reach of a grout column would be of interest.

Paper #1.32 by Villarraga describe a laboratory and field study carried out to examine various factors that affect the dynamic properties of tropical soils from Medellin in Colombia. Factors examined included soil origin (residual, sedimentary) and index properties. For the different soils analysed various empirical correlations were established between the shear wave velocity obtained in the field by cross-hole tests and the index properties: natural water content, SPT number, % of fines, Atterberg limits and effective vertical stress. These correlations were ranked as recommended, acceptable and not acceptable.

Laboratory test results from dynamic triaxial and torsional tests with conjunction with bender elements showed that soil origin and parent rock type in the residual soils are the most significant factors affecting the shear modulus degradation curves. Residual soils from metamorphic rocks have more important decrease of shear modulus (G) with strain than those from igneous rocks. The normalised G and damping ratio (D) values under different strain levels were compared with the Dobry and Vuccetic curves in function of plasticity index. They found a good agreement for the alluvial soils, whereas for the residual soils and high weathered colluvial soils the normalised G values fall in a low narrow zone of plasticity index, being the influence of this index not as clear. For the damping ratio values an important scatter in results for the residual soils do not lend them to any consistent analysis.

Paper #1.36 by Thevanayagam and Liang proposed relations that give low strain shear wave velocities/shear moduli for silty and gravelly (mixed) soils. These equations are expected to be of value in providing preliminary estimates of these characteristics for, for example, seismic analyses. The equations are said to represent an improvement over existing equations that are based on overall void ratios or relative densities. When using the proposed equations a soil is treated as a mix of two components of markedly differing grain size. Two new void ratios are defined (one for each component) that are said to represent, more precisely than does the overall void ratio, the grain contact density of mixed soils. Thus, the authors believe that the proposed equations give improved estimates of shear moduli/shear wave velocities for such soils. The authors show test-based comparisons for mixed soils that suggest that the proposed equations result in better estimates of these characteristics than the existing equations. Given the importance of soil structure to the characteristics of interest, representing structure more completely would be expected to result in improved estimates. At the same time, more effort would be required in establishing values for the parameters of the proposed equations.

Paper #1.38 by Riemer et al. describes a new device that can be lowered into a mud-filled borehole to measure in situ dynamic shear modulus and damping of soils. After lowering this device, the vertical stress is restored at the bottom of the hole and an annular portion of the soil is removed producing a freestanding soil column without significantly relieving the in situ stress. A membrane is rolled down around the specimen and the specimen is cyclically excited in a torsional mode. In this study the authors report the feasibility of this device using simulated field conditions test set up in the laboratory. The measured shear modulus and damping data compares well with the measurements made by others using conventional laboratory test devices. While this study shows the feasibility of such a device, the original aim of this research, viz- the utility of this device to reconcile differences between dynamic shear modulus measured using conventional laboratory tests on "undisturbed" samples and in situ data from field wave velocity methods is yet to be tested.

Paper #1.44 by Zoghi presents a discussion of the cyclic degradation characteristics of samples of clay-shale subjected to cyclic loads. It appears that the author's interest in this subject matter is in evaluating the stability of slopes during earthquakes. The author provides a background that summarizes how degradation characteristics of soils are described mathematically. Then, results are presented from a laboratory cyclic test conducted on a clay-shale sample that shows cyclic degradation characteristics. The author indicates that the results presented are consistent with corresponding results presented in the literature. The author also briefly discusses tests on clay-shale samples in which, before application of the cyclic loading for establishing degradation characteristics, the samples were displaced bi-directionally sufficiently to strain the samples to reach their residual strengths. In these cases, the samples were found to show considerably less degradation than the samples that were not prestrained. The results presented by the author do not appear to show any unusual behavior that has not been previously observed.

Paper #1.47 by Groiewski and Zeng report an experimental setup which uses bender elements to measure shear wave velocities in four shear planes in a saturated clay specimen under different consolidation pressure. The data has been used to investigate the anisotropy of soil stiffness in clay due to anisotropic stress conditions. The measured G_{max} is compared with those predicted by empirical formulas and found to compare well. Shear velocity measurements in the different planes were also used to estimate the K_0 vale of clay under different consolidation pressure and compared with theories. With certain ad hoc modifications the results were found to compare well. The further investigates the effect of repeated loading on G_{max} and K_0. It was found that a strengthening effect is apparent in 1-D consolidated specimens during repeated loading.

Paper #1.53 by Anand et al. used the Continuous Surface Wave System (CSWS) to obtain field profile of shear modulus of a residual soil site and a soft soil site in Singapore. After a very comprehensive description on inverse analysis of field dispersion curve by different methods, they found for the study sites that CSWS can provide shear modulus profiles up to a depth of 20m in residual soils and up 8m in soft soils. Shear wave velocity profile from cross-hole tests in the soft soil site is in a good agreement with that from CSWS, despite the limited penetration depth of the latest.

They also found that a 2D axisymmetric FE model could be used to obtain a synthetic dispersion curve, which matches well with the field dispersion curve for both sites. The selection of a suitable inversion tool in conjunction with stratigraphic information is the key feature to derive the correct shear modulus profile for a site, despite the fact that CSWS being an inherently averaging technique not reflecting minor variations in strata thickness as in the borehole log.

Paper # 1.61 by Rathje et al. reports on the development of an in situ testing methodology for the determination of nonlinear soil properties. The test consists in applying a static and a dynamic load on a footing located over an array of geophones. The static load controls the initial effective stresses on the soil, while the dynamic load imposes shear and normal strains of varying magnitudes on the soil. The testing reported comprises a test sequence guided towards the determination of the influence of effective stresses and strain amplitude on the constrained modulus of the soil. Stresses in the soil are determined from elastic solutions. Strains are calculated from the acceleration time histories measured by the geophones. Results at shallow depth show a power-law relationship of small strain modulus with effective stress in the direction of wave propagation. This trend was not observed at larger depths, presumably from a poor estimate of initial stresses. The reduction of constrained modulus with increasing strain is in accord with variations of shear modulus with shear strains published in the literature. The proposed in situ test will address the current need for in situ verification of laboratory measurements of nonlinear soil behavior. The full development and validation of such a procedure will undoubtedly benefit the earthquake engineering profession.

Paper #1.64 by Flores & Romo presented the variation of shear modulus (G) and damping ratio (D) with strain level obtained by resonant column test method. The soils tested were tailings from two different sites in Mexico reconstituted by compaction with different water contents and relative compaction.

Results are consistent with previous findings showing that the increase of relative compaction and confining pressure increase the shear modulus, while damping ratio decreases. They also identified a volumetric strain threshold, which increase with the increase of confining pressure and the relative compaction.

The G and D values obtained under different strain levels were compared with a Masing type model (Davidenkov's model) and with neural network predictions. Both techniques performed quite well, mainly for the shear modulus, with a better prediction by neural network for the shear modulus exceeding about 60 MPa.

Paper #1.66 by Stevens et al. reports of a centrifuge study where dynamic shear modulus is determined using recorded acceleration history at various depths. The acceleration time history at two adjacent depths is double integrated and used to determine the stress-strain history and thereby shear modulus-strain relationship. The results are somewhat sensitive to the numerical scheme and time-window employed to determine the modulus and the strain level. They also report a method for conducting shear wave velocity measurements in the centrifuge. The back figured modulus data corresponding to a strain level of 10^{-2} % normalized with the maximum shear modulus obtained from shear wave velocity measurements compares well with the modulus degradation curve reported in the literature (Seed and Idriss (1970). It is not clear whether the sensitivity of the time-window affects the ability to determine the modulus data over a large range of strain.

Paper #1.67 by Elgamal et al. presents shearing stiffness and damping characteristics inferred for a heavily instrumented centrifuge sample of dense sand subjected to simulated earthquakes. The material presented bears on predicting and understanding the behaviors of soil deposits during earthquakes. Apparently, conditions corresponding to one-dimensional earthquake site response analyses were sought in the simulations. The simulated earthquakes induced strains in the tested sample estimated to be small to moderate. The stiffness and damping characteristics were inferred using system identification techniques centered on a linear viscous (SBEAM) and an equivalent linear (SHAKE) one-dimensional earthquake site response analysis procedure. Both measured and computed motions were filtered to isolate behavior at the fundamental mode. On the basis of comparisons with available information, the inferred characteristics seem reasonable. When using these characteristics in the site response analysis procedures, computed filtered accelerations were reported to agree closely with filtered accelerations measured at the center of the sample. In their future studies that are to address behavior at higher strains, the authors may wish to consider using true nonlinear as well as equivalent linear and linear site response analysis procedures.

Paper #1.68 by Ozutsumi and Iai proposes a method for adjusting the damping constant of each spring in the multiple shear spring model. This model is used to simulate the soil behavior during earthquakes. The damping constant is adjusted by making it a function of the displacement at the unloading point of the spring, and could be expressed by a polynomial composed of functions similar to the hyperbolic type function. The model is incorporated in the FLIP program.

Paper #1.71 by Marosi and Hiltunen presents an inversion protocol for the spectral-analysis-of surface-waves (SASW) used in characterizing the variation of the shear modulus with depth. The developed method was used on different curves from a wide variety of test sites. The predicted dispersion data of the shear wave velocity profiles had reasonable correlation with the experimental data. The main advantage of the developed protocol that it is manageable for an inexperienced user while the current SASW procedure needs an experienced user to produce an accurate shear wave velocity profile.

LARGE STRAIN PHENOMENA

Paper #1.03 by Uchida et al. carried out very interesting investigation on "undisturbed sand samples" obtained after freezing the ground to study the effect of anisotrophy on drained and undrained cyclic behavior. A series of drained compression and extension tests were performed. Separately, they carried out a series of undrained cyclic tests on the undisturbed sand samples. They concluded that the effect of anisotropy on both internal friction and liquefaction resistance is negligible. The deformations appeared to be more in samples with vertical axis parallel to the bedding than those in the perpendicular.

Paper #1.04 by Koseki et al. conducted a series of undrained cyclic torsional shear tests to investigate the effects of initial confining stress level on liquefaction resistance of sand. Hollow cylindrical dense specimens with outer diameter of 10 cm, inner diameter of 6 cm and a height of 20 cm are prepared with two kinds of sand. The tests were performed for initial confining stresses of 4.9, 9.8, 98 kPa. For both sands, the authors concluded the liquefaction resistance decreased with increasing initial confining stress. The reviewers believe that stress range is too small to arrive at a meaningful conclusion.

Paper #1.06 by Yimsiri and Soga numerically investigated the effects of soil fabric on undrained behavior of sands using the Discrete Element method software PFC3D by *Itasca*. A tensor based on the contact normal distribution is introduced as an index to describe the soil fabric quantitatively. It has been found that the degree of fabric anisotropy has a profound influence on the undrained response of sand. For example, the DEM analysis shows that the specimen, which has contact normal distribution concentrating in the vertical direction has higher stiffness and is more dilative when subjected to subsequent triaxial compression shearing. It has, however, lower stiffness and is more contractive when subjected to subsequent shearing. The numerical results are qualitatively consistent with the published experimental data on the effect of reconstitution methods and of preshearing on the mechanical behavior of sands especially in the undrained condition. The study is further evidence that it is necessary to account for the effects of soil fabric in the description of undrained liquefaction behavior of sands.

Paper #1.09 by Vakher presents relations proposed for estimating the resilient modulus of subgrade reaction for a peat soil supporting large concrete plates. The relations are said to be of value to the design of connections between the concrete plates that make up roads in rural areas. Relations are presented for strata consisting of 1) a layer of peat alone and 2) a layer of sand overlying a layer of peat. The relations are based on both field and laboratory tests. In the field tests, a vehicle was driven over concrete pavement plates and appropriate vertical displacements were measured. Factors that differed among tests included the load produced by the vehicle and the layering of the supporting soil. The field circumstances were simulated in the laboratory using a specially developed laboratory apparatus. The laboratory results provided the basis for the proposed equations for estimating the resilient modulus of subgrade reaction. The field test results were used to calibrate the laboratory test-based equations. Fairly significant correction factors (3 and 4) were needed to predict field test results using these equations. Thus, caution should be taken in applying the proposed equations to considerably different conditions.

Paper #1.16 Shahnazari and Towhata investigated “the volume change” due to cyclic loading under “drained cyclic simple shear” condition. Possible correlation of plastic shear energy with volumetric strain and effects of confining pressure, initial anisotropic consolidation and strain amplitude on the correlation was studied. Test results showed that volumetric strain of sand under different initial confining pressures was almost same. Such conclusion was subjective. The testing program was limited and lacked focus. It is not clear that the influence of void ratio had been considered.

Paper #1.20 by Kammerer et al. conducted a limited series of tests on Nevada sand in cyclic simple shear device. This testing was intended to study the complex influence of initial static shear (sloping ground) and the soil fabric. The testing and the results presented in the paper are limited despite the complexity of these two factors in sand liquefaction. However, they have shown that with the increase in initial static shear (alpha), the excess pore pressure ratio decreased significantly in dense soils and of course the cyclic shear strain. Under these conditions, liquefaction resistance of the sand also would have increased tremendously, which the authors have not discussed. Also results of a limited testing on fresh and reconsolidated samples were presented to indicate that strain level reached for the freshly consolidated fabric would be larger than that occur in the reconsolidated sand. Although this is true, the General Reporter (s) are of the view, that with or without the influence of fabric, dense sand with a change to its initial state or " stress-density history” due to reconsolidation could produce lesser cyclic strains and higher cyclic strength given the other conditions are the same.

Paper #1.33 by Polito has reviewed "Plasticity based liquefaction criteria” and he has provided some interesting conclusions and recommendations. These criteria are used to separate soils that may be considered non-liquefiable from those susceptible to liquefaction based on clay content, plasticity and density of the soil. The author used the results of a parametric study of the effects of plastic fines content and plasticity on liquefaction susceptibility of sandy soils. Most of the criteria were found to have conservative requirements in terms of soil plasticity. Based on his review, he concludes that one parameter which consistently separates soils susceptible to flow liquefaction from soils, which undergo cyclic mobility, is the soil plasticity. In closing, he concluded that a soil's behavior during cyclic loading can be predicted based upon its Atterberg limits.

Paper #1.49 Taboada-Urtuzuastegui and Romo carried out "an experimental study to assess the shear modulus degradation by fatique of Mexico City clay" and arrived at some interesting conclusions for the threshold of plastic yielding after the elastic response. The study was conducted using cyclical triaxial tests on undisturbed clay samples. The threshold strain was determined to be about 2.25 % for Mexico city clay that was investigated. Below this number, the material does not generally produce any excess pore pressure or plastic strains and degradation. The reviewers believe that the tests have lot of significance. These tests and the high threshold strain of the Mexico city clay further confirms that it has the potential for large elastic yielding and more resilience to withstand earthquakes as compared to other materials such as sands or low plasticity clays.

Paper #1.51 by Pillai and Muhunthan reviewed, based on critical state soil mechanics framework, the mechanisms of the influence of confining stress and initial static shear on liquefaction. Results showed that constant cyclic resistance ratio lines follow contours of parallel lines of constant initial states, while this relationship was different for different materials. They demonstrated as well the importance of future research focusing on the fundamental properties of soils such as λ, κ and M to obtain more realistic correlation.

Paper #1.52 by Berghe et al. presents the results of cyclic triaxial (TXS) and simple shear (DSS) tests on a dense Brusselian sand ($Dr \approx 85\%$). The range of cyclic shear strains for the undrained TXS tests is 0.1% to 6%. The confining stress is modified to maintain a constant mean stress. The constant volume DSS tests are performed on an NGI simple shear device using a wire-reinforced membrane for confinement. The range of cyclic shear strains is 0.25% to 9%. The pore pressure and stress-strain behavior observed in the TXS and DSS tests show remarkable similarities. Based on the test results, a model used to predict the shape of the hysteresis loops in DSS tests is presented. The model uses the backbone curve from a monotonic test; a single degradation parameter that is a function of soil type, relative density, consolidation stress, and strain amplitude; a relationship between the secant shear modulus and the energy dissipated during the corresponding cycle for a given strain amplitude; the Masing rules. The proposed model implies that the shape of the hysteresis loops is not arbitrary, but is a function of the maximum shear observed in each loop. The model applies only to dilative soils.

Paper #1.55 by Moriwaki et al. carried out cyclic triaxial consolidation tests on clay samples cured at room temperature as well as those cured at high temperature. The pre-consolidation in the triaxial was carried out under K0-condition to simulate the consolidation history of naturally deposited clay. It was found there exist some differences in cyclic triaxial behavior in the samples cured under high temperature from that at the room temperature. Also the authors conclude that both volumetric and shear deformation under cyclic loading are much larger than those under static loading for stress states above the pre-consolidation level.

Paper #1.56 by Kokeguchi et al. presents results from cyclic torsional shear tests on sands followed by monotonic shearing simulating post-liquefaction deformations. The aim of this study was to determine whether post-liquefaction behavior is strain rate dependent. They found that the post-liquefaction stress-strain curve showed an initial soft behavior followed by stiff response. The initial softer response was found to be the result of accumulation of a thin layer of water underneath the loading cap on top of the specimen. The subsequent stiffer response was interpreted to be the response of the sand after stabilizing/resedimentation of the grains under gravitational load following liquefaction. Neither the initial portion nor the stiffer response was found to be strain rate dependent. A second set of test was conducted using Styrofoam grain with a specific gravity close to that of water. The low specific gravity prevented the settling of grain under gravitational load and thus maintains the granular material in floating stage following liquefaction. Again no strain-rate dependent post-liquefaction behavior was observed.

Paper #1.57 by Shun-ichi et al. carried out an interesting testing program to study the effect of K0-consolidation on liquefaction strength of silty sand using a self-boring lateral load tester (SBLLT) and a flat -diratometer (DMT). A series of cyclic undrained torsional shear tests under the plane strain condition on undisturbed soil samples. The effect of K0 consolidation and cyclic stress condition on cyclic shear strength as a cyclic shear stress ratio at a specified double amplitude shear strain such as 1.5%, 3.0%, 7.5% and 10% . It was observed at high shear strain level (7.5%), the cyclic shear strength in cyclic torsional tests and cyclic triaxial tests was small as compared to that at low shear strain level (3%).

Paper #1.62 by Sasaki et al. used small model tests to study of suspended soils in post-liquefaction state based on Stoke's Law. For this purpose, glass bead particles were used as model ground material. The test results indicated that the glass bead grains were suspended in pore water at the instant when complete liquefaction was brought about to the layer, then they began to settle in the water. The particle movement was observed to be much slower than estimated by Stoke's equation for sedimentation of a single particle. From this, the authors proposed a predicting method to obtain the compressibility of liquefied sand. The reviewers believe that the simulation of liquefied soil in the model is totally unrealistic to predict any meaningful settlement of post-liquefied soils in the field.

ELASTO-PLASTIC PHENOMENA

Paper #1.01 by Li conducted experimental investigations of dynamic behavior of soils under periodic loading to investigate soil-elastic parameters under confining pressure and loading frequency. It was concluded that both confining pressure and loading frequency affect nonlinearity of soil stress-strain relations and cell pressure plays a more significant role in nonlinear behavior of stress-strain curves. Also it was concluded that soil viscosity is related to cyclic loading and cell pressure. The author's conclusions are interesting but need further investigation.

Paper #1.15 by Wanda and Robert Henke presents an automated analysis procedure for extracting the soil properties from the results of in situ testing using the "impulse shear test". The test is used to estimate the soil characteristics in terms of the low strain shear modulus, secant shear modulus reduction curves, and damping ratio curves needed in earthquake engineering analysis procedures. The use of the automated analysis procedure was demonstrated by interpreting results of impulse shear tests conducted at the silty clay site of the University of Massachusetts at Amherst.

Paper #1.27 by Asonuma et al. examines the mechanical behavior of volcanic grounds by in-situ and laboratory tests. It also quantifies the deformation behaviors and their dependencies on strain level. The field-testing consisted of cone penetration test (CPT), standard penetration test (SPT), and seismic cone penetration test (SCT). In addition, a series of cyclic triaxial test was conducted in the laboratory. The measurements have shown that the shear modulus at small strain was independent of void ratio.

Paper #1.41 by Luong introduces infrared thermography as a non-contact and non-destructive technique that conveniently offers the possibility of evaluating energy-dissipating ability of soil. Measurement of dissipation in soils has remained a difficult problem and therefore this work is to be commended. The work aims to interpret the physical and mechanical properties of particulate materials at the microscopic level in relation with the deformation mechanism occurring at the granular level. Infrared thermography readily evidenced the intrinsic dissipation of fine sand caused by friction between grains. The energy dissipation mechanism influences the wave speed, intergranular attenuation, and dispersion through particle contacts. They determine the proper stiffness and damping characteristics that influence the wave speed and intergranular wave attenuation and dispersion.

Paper #1.73 by Khusanov reported results of a study into the behavior of grounds and rock mass under explosive loads using a new model of deformation ground and rock mass accounting structural destruction of grounds. The mechanical characteristics of the ground are considered as functions of the degree of structural destruction (on the second invariant of the deviator of deformation). The explosion is simulated by a hemispherical cavity cut from the half-space ground with loading applied from its sides. The problem is solved numerically using finite difference techniques. The solution provides the dimensions of the craters and outburst ground as well as the zones of destruction of ground and rock mass.

GENERAL DISCUSSION

Recent occurrences of earthquakes (El Salvador, Taiwan, Turkey, Kobe, Los Angeles, San Francisco) and the tremendous loss of life and destruction of property associated with them emphasizes the need for better deterministic tools to predict the response of soils under dynamic loading. Research is vital for a comprehensive understanding of the mechanics of a host of seismic problems including site response to ground motion, liquefaction, and soil structure interaction before design guidelines can be developed. Soil behavior under static and dynamic loading is strongly dependent on:

i) direction of loading/stress path (e.g. compression, extension, and simple shear)
ii) fine contents/plasticity characteristics
iii) structure/meta-stable collapse
iv) anisotropy/angularity

The diverse experimental methods, analysis, and modeling techniques discussed in the general report provide some guidance towards identifying the influence of the above factors on soil response. However, most methods and equations developed are empirical and in general follow established guidelines. Ad hoc modifications to existing equations have been made by some authors to suit their data better. Caution must be exercised before using such methods for conditions other than for which they were developed.

The distribution of the papers indicates that the majority of the research is confined in the area covering small strain phenomena. There have been some advances made in the measurement of shear modulus, its degradation, and damping characteristics. Most of these are with the use of bender elements and the use of SASW techniques. Small strain phenomena are also where most authors have tended to follow established research methodology without paying much attention to the factors discussed above. Notable exceptions to this rule are the papers by Thevanayagam and Liang (Paper #1.36) which tends to include two new void ratios in studying shear waves, and the one by Sincrarian et al. (Paper #1.28) which models the nonlinear dynamic response by the use of a discrete element code. Such approaches may lead to realistic analysis of soil response under dynamic loading in the future.

Pillai and Muhunthan (Paper #1.51) emphasize the use of critical state soil mechanics principles in determining the influence of "fines content", initial static shear stress and confining stress in problems involving large strain phenomena such as soil liquefaction.

Liquefaction of soils involves three distinct phenomena; strain accumulation (recoverable) in the elastic domain leading to a threshold where plastic strains (non-recoverable) begin to accumulate with pore pressure build-up. In the plastic domain, with continued cycling of shear stress, strain softening (or large accumulation of strains) with decreasing resistance would take place leading the soil mass to "a liquefied state". Such reduced resistance of the soil mass may or may not be adequate to support the foundation or the earth structure, it constitutes. Often, the cyclic shear stresses induced by earthquakes are small and stay within the elastic domain. The soil-structure would exhibit no permanent effect at all. When cyclic shear stresses are large enough to enter the plastic domain, large strains and permanent effects could be exhibited by the structure.

The authors (Paper #1.51) distinguish plastic yielding of loose alluvium (ductile-stable yielding) from that of loose moist-tamped sands/marine deposits (collapsible-unstable yielding). For the same material, shear characteristics as well as the influence of initial static shear and confining stress could differ for stable ductile yielding from the unstable collapse yielding. For example, post-liquefaction residual strength of moist-tamped material (collapsible-unstable yielding) is generally very small compared with water-pluviated alluvial material (stable yielding) under similar void ratio-confining conditions. Therefore, the mode of deposition, the initial state of the soil and the stress-path of subsequent yielding process under cyclic loading can have significant influence on liquefaction and post-liquefaction strengths.

Earthquakes can induce cyclic stresses in foundation soils that may not be large enough to cause large (plastic) non-recoverable strains. Often that is the case when the earthquake induced cyclic stress ratio in the soils is less than about 0.07 and strains less than 0.1% (threshold strain). The threshold strain could be as high as 2.5 % for Mexico city clays (paper #1.49) suggesting that even the elastic response is significantly influenced by "fines content" similar to the plastic response. In a high seismic environment like Mexico City, the large elastic domain provides additional safety against small earthquakes or cyclic stresses. Future research must take such factors into consideration rather than confining itself to specific conditions in the laboratory or field.

In conclusion, the General Reporters believe that significant research using fundamental soil mechanics is needed. This should be encouraged in the small strain phenomena as well as in large strain phenomena areas of plastic yielding leading to liquefaction and residual state due to cyclic stresses. Determining the influence of "fines content" and initial static shear on liquefaction strength and residual strength remain crucial for the development of earthquake resistant measures.

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