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General Report Session 3: Deformation and Liquefaction of Sands, Silt, Gravels and Clays

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Deformation and Liquefaction of Sands, Silt, Gravels and Clays

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INTRODUCTION

It has been almost 27 years since the damaging earthquakes of 1964 which occurred in Niigata, Japan and in Alaska, USA, focused the geotechnical engineers' attention to liquefaction as a major problem in earthquake engineering. Considerable research and studies have been conducted on the subject of earthquake induced liquefaction since that time and these have included field observations, laboratory experiments and model tests, and theoretical studies. Progress in understanding the liquefaction phenomenon, in the assessment of liquefaction potential, and in the solutions to mitigate the liquefaction hazard has been made, yet the problem remains controversial in many respects, as reflected by the many stimulating papers presented in this session.

The word "liquefaction" has been associated with many phenomena observed in the field during and after earthquakes such as sand boils, flow slides, lateral spreads, loss of bearing capacity and porewater pressure rise. In laboratory tests, liquefaction has been defined in several ways relating to pore pressure buildup under undrained cyclic straining or loading, or the development of a specified amount of shear strain in a fixed number of cycles of loading. Laboratory studies have also shown that the liquefaction phenomenon can be divided into three different behaviors, namely, true liquefaction, limited liquefaction and cyclic mobility. In theoretical studies, liquefaction occurs when the seismic-induced cyclic shear stress exceeds the cyclic shear resistance, or when the seismic porewater pressure increases to equal the effective stress. To compare the results from different papers, one must bear in mind the different definitions used by the various authors.

Liquefaction-caused failure is really the result of excessive permanent deformation, e.g. tilting, settlement or heave of structures, excessive slumping or distortion, and sliding of slopes. Liquefaction-induced ground deformation is receiving more attention in the last decade. Soil failure due to liquefaction was the most dominant cause of damage in the recent M 7.7 Luzon earthquake of July 16, 1990 in the Philippines.

Remedial measures or ground improvement techniques to reduce the liquefaction hazards are becoming more common in recent years, not only for seismic rehabilitation of existing sites but also for newly developed sites. Refinements in equipment and techniques of existing methods are being developed. As well, new methods of ground improvements are being introduced. The M 7.1 Loma Prieta earthquake of October 17, 1989 showed convincingly that liquefaction hazard can be avoided or effectively mitigated by soil densification prior to earthquake.

CLASSIFICATION OF PAPERS

The 43 papers in this session can be conveniently divided into the following categories and subcategories:

1. OBSERVATION AND MECHANISM OF LIQUEFACTION
   - Field Observations (4 papers)
   - Laboratory Tests (10)
   - Theoretical Studies (3)
2. ANALYSIS AND EVALUATION OF LIQUEFACTION POTENTIAL
   - Field-based Approaches (6)
   - Laboratory-based Approaches (4)
   - Dynamic Analyses (5)
   - Mathematical Approaches (2)
3. RESIDUAL STRENGTH (1)
4. PERMANENT DEFORMATION
   - Settlements (3)
   - Horizontal Displacements (2)
5. REMEDIAL MEASURES (3)

The authors represented 7 countries: Canada, China, India, Japan, Malaysia, Thailand and USA.

OBSERVATION AND MECHANISM OF LIQUEFACTION

Field Observations

The first of 4 papers in this subcategory, Paper 3.6 by Agrawal, records the liquefaction-induced damages from two moderate recent earthquakes in India: the M 5.6 Cachar earthquake of 1984 and the M 6.5 Great Nicobar earthquake of 1982. The affected areas are at short distances from the epicenters. The author suggests that the duration of shaking was insufficient to generate pore pressure to cause liquefaction. Instead, he proposes a physical model to explain the observed upthrow of objects and postulates that the "quick-sand" phenomena were due to disturbance of soil structure caused by impulsive forces associated with the rupture at source, rather than due to seismically-induced shear stresses in the soil. It would be interesting if the author provides some information on the recorded or estimated ground motions and the duration of strong motion at the affected sites.

Paper 3.40 by Liu, Wong and Wang documents 19 cases of liquefaction-induced river bank slides or lateral spreads observed after the Haichen earthquake (1975, M 7.3) and the Tangshan earthquake (1976, M 7.8) in China. The main characteristics of the 19 recorded cases, including the type of liquefied soil, width of lateral spread zone, permanent displacement, ground slope and inclination of base of liquefied layer, and the type of damage, are given. The authors found that the widths of the lateral spreads vary widely from 40 m to 600 m with a ratio of the width of lateral spread to depth of river ranging from 15 to 60. The ground surface in many cases is almost flat and the inclination of the base of the liquefied layer is 1% to 2% or even less. The paper should make a worthwhile contribution to the existing data base on field liquefaction, particularly if the authors can indicate how the Chinese Intensity scale is related to the Modified Mercalli Intensity scale or to peak ground acceleration.

Paper 3.44 by Jain, Tripathi and Agrawal reports on the geotechnical damage in India due to the M 6.6 Bihar-Nepal earthquake of 1988. The field observations include liquefaction, embankment subsidence and cracking, damage to bridge piers, abutments and wing walls, and landslides. Apparently, the observed damage pattern is similar to that of an earlier M 8.4 1934 earthquake in the same vicinity.

The last paper in this subcategory, Paper 3.54 by Shen, Li and Wang, presents pore pressure data obtained from downhole arrays at the Lotung seismic model study site in Taiwan during two significant earthquakes in 1986. The first is a M 6.2 event at an epicentral distance of only 6 km from the site, while the second event is M 7.0 at 80 km away from the site. Although the intensity of ground shaking at the site was the same for both earthquakes, the porewater pressure response records from the two earthquakes were different, even for several sensors at the same depth in the same soil layer. It was concluded that field pore pressure response is influenced by local soil conditions and that the pore pressure data should be examined for general trend of the response, rather than studying the response of a specific record. The authors then used a nonlinear effective stress finite element procedure to analyze the response of the stratified level ground under multidirectional earthquake loadings. They found reasonably good match between the calculated and measured average pore pressure responses. It should be noted that the observed maximum induced pore pressure rise is less than 30% of the effective overburden pressure.

Laboratory Tests

Of the 10 papers in this subcategory, the first 5 discussed below are based on results of triaxial tests. Paper 3.1 by Xia presents the results of cyclic triaxial tests conducted on reconstituted fine sand samples taken from a damsite in China. The test were conducted to investigate the effects of initial pore pressure and degree of saturation on the liquefaction resistance of the sand, for samples tested isotropically under the same effective stress. The test results show that liquefaction resistance, as characterized by the cyclic deviator stress ratio for a given number of loading cycles, increases with increasing initial pore pressure and decreases with increasing degree of saturation. The author attributes the former phenomenon to the effect of porewater pressure on interparticle forces and suggests that Terzaghi's effective stress principle is not strictly valid. The author further suggests that for liquefaction tests, the backpressure technique not be used to enhance the degree of saturation of the test samples. The author's findings have important implications, and similar tests should be independently conducted by others to confirm or disprove these findings.

Paper 3.14 by Ullrich, Roberts and Thacker presents the results of cyclic triaxial tests on fine coal refuse materials and describes the use of the test results in a simplified effective stress slope stability analysis of coal tailings dams subjected to earthquake loading. The procedure employs the conventional method of slices approach in which the earthquake loads are represented by a pseudostatic force applied to each slice. The excess porewater pressures estimated from the laboratory tests are added to the static pore pressures in the analysis. Anisotropically consolidated cyclic triaxial test results of the fine sand to silt sized materials are presented for six sites in the Western Appalachian region. The data appear to suggest that the fine coal processing technique influences the measured pore pressure response of the fine refuse materials.

Hyodo, Murata, Yasufuku and Konami in Paper 3.36 investigate the undrained cyclic triaxial behavior of Toyoura fine sand samples subjected to different initial static and cyclic shear stresses. To calculate the cyclic strength, they used a residual axial strain of 10% as the failure criterion for both reversal and non-reversal cyclic stress conditions. An empirical procedure for predicting residual pore pressure and residual axial strain in each stress cycle is proposed, applicable to anisotropically consolidated soil subjected to variable amplitudes of cyclic shear stresses.

Paper 3.19 by Nishio and Tamaoki presents an interesting laboratory testing program in which shear wave velocities were measured during large scale triaxial compression tests conducted on diluvial gravel samples. Both saturated reconstituted and undisturbed samples, obtained by the in-situ freezing method in Japan, were tested. The special apparatus allows shear wave to be generated by tapping the top cap of the specimen and the wave is detected by a series of accelerometers attached to the side surface of the specimen. The changes in shear wave velocity during isotropic consolidation and during drained triaxial compression tests were monitored, and unique relationships were obtained relating shear wave velocity to stress ratio. The samples tested were 300 mm in diameter and 600 mm in height. It would be interesting if the authors can provide some indication of the distribution or variation of shear wave velocities along the height of the sample.

Paper 3.43 by Kuwano and Chen presents results of drained static and cyclic triaxial tests on compacted greywacke sandstone obtained from a damsite in Thailand. The tests were conducted to investigate the effects of variations in the degree of saturation, initial shear stress, applied loading pattern, and fines content on the axial deformation and strength characteristics. The paper is concerned with train loading on railroad ballast and consequently, the cyclic loading patterns involve compression loading with no shear stress reversal.

The sixth paper in this subcategory, Paper 3.30 by Dev and Kaniraj, provides results of cyclic simple shear tests on some sands in India. Five different gradations of Ennore sands and one sample of Badarpur sand were tested. The samples were reconstituted by dry pluviation method to an initial relative density of 50%. The actual relative densities varied from 46% to 63% during sample formation and post-consolidation relative densities varied from 50% to 75%. Test results for Ennore sands suggested that the liquefaction resistance increases with increase in Fineness Modulus, as well as with increase in a grain size and gradation factor, R. The authors found that the above empirical correlations, however, could not reliably predict the cyclic strength of the Badarpur sand. It is not clear how the authors corrected, if any, for the difference in relative densities of the samples tested.

Figueroa and Dahisaria in their Paper 3.17 present the results of some cyclic hollow cylinder tests on Reid Bedford sands. The accumulated energy per unit volume was calculated from the observed hysteresis loops up to the point of liquefaction. Simple relationships between normalized pore pressure and unit energy required to induce liquefaction were developed from the test results. Different regression lines were obtained for different effective confining pressures.

Paper 3.46 by Dakoulas and Sun presents a laboratory study to investigate the effect of principal stress rotation on pore pressure buildup and deformation characteristics of contractive fine Ottawa silica sand. Three types of cyclic tests were conducted in a specially designed triaxial cell: (1) cyclic axial test performed on a solid specimen, (2) cyclic torsional simple shear test performed on a hollow cylinder specimen, and (3) circular rotation of principal stresses with constant deviator stress performed on a hollow cylinder specimen. Comparison of test results indicates that the rate of excess pore pressure buildup and rate of accumulation of plastic deformation are faster in the rotational shear test than in the other two cyclic tests. These conclusions are in agreement with results from a similar study conducted by Ishihara and Towhata (1982) on Japanese Toyoura sand.

Paper 3.48 by Fei, Woods and Wu presents the results of resonant column tests on soft alluvial soils from Shanghai, China. Modulus reduction curves and damping versus shear strain curves for sand and clay are presented, together with equations from regression analyses of the test data. Hardin and Drnevich type empirical equations for low strain shear modulus were also derived from the test results.

The last laboratory experimental paper, Paper 3.37 by Miyajima and Kitaura, describes shaking table tests of a model pipeline embedded in saturated loose sand contained in a box. The pipe-soil system was shaken sinusoidally in the axial and transverse directions, and force, relative displacement, pore pressure and acceleration were measured during the shaking process until liquefaction occurred. Soil spring constants for a bilinear soil model were derived from the force-relative displacement data. Relationships between the spring constants and the effective stresses during dynamic loading are presented.

Theoretical Studies

The first of three papers in this subcategory is Paper 3.57 by Zhang and Hu. The authors propose an elastoplastic model for liquefaction in sand incorporating Rowe's stress dilatancy relationship and a porewater pressure generation model. They show good agreement between calculated and predicted results from drained and undrained laboratory cyclic tests.

Paper 3.67 by Zhang and Xie proposes an uncoupled pore pressure generation and dissipation model, much like Seed's model, to calculate seismic pore pressure in saturated sand. Results of laboratory cyclic triaxial tests were used to verify the model trends.

Paper 3.70 by Wu discusses criterion for liquefaction in sands during earthquake. Cyclic stress equations during liquefaction were derived.

ANALYSIS AND EVALUATION OF LIQUEFACTION POTENTIAL

Field-based Approaches

The first of six papers in this subcategory, Paper 3.7 by Valera and Kaneshiro, describes a liquefaction study for a rubber damsite underlain by alluvial sands and gravels in California. The authors present a good review and critique of published case histories in which earthquake-induced liquefaction of gravelly deposits had supposedly been observed. Their assessment of liquefaction potential is based on the simplified Seed's Standard Penetration Test (SPT) method. The effect of gravel content on the measured SPT blow counts was investigated by recording blow counts for every 0.1 ft of penetration, and by comparing grain size curves of SPT samples with those of bulk or bag samples obtained from excavations.

Paper 3.13 by Reyna and Chameau presents the results of liquefaction assessments using the dilatometer test (DMT) at three sites in the Imperial Valley in Southern California. Existing empirical DMT liquefaction correlations are examined with respect to the known liquefaction behaviors at these sites due to earthquakes in 1979 and 1981. The DMT based liquefaction potential assessment is further compared to SPT and cone penetration test (CPT) based assessments at one of these sites. The authors then propose a tentative boundary curve for liquefaction potential evaluation using the DMT K_d parameter for M 5.5 to 6.5 earthquakes. They also suggest that a combination of dynamic and static (or quasi-static) dilatometer tests may provide a more promising index for further studies.

Paper 3.18 by Martin, Tsai and Arulmoli presents a practical approach to the evaluation of liquefaction potential and site remediation as applied to a large housing development in Southern California. Liquefaction potential assessments based on CPT and SPT were conducted and compared to the results of effective stress dynamic analysis using the DESRA2 program. The potentially liquefiable soils were identified by conducting a series of CPT soundings and SPT boreholes. The depths of ground improvement required were established to limit ground settlement due to liquefaction to less than 2 inches or to prevent surface manifestation of liquefaction, whichever is the greater depth requirement at the test locations.

Paper 3.26 by Lavania, Mukerjee and Sharma describes the evaluation of liquefaction potential at a damsite in India. Empirical approaches based on laboratory and field SPT data indicated that the site would not liquefy. To determine the reduction in shear strength with pore pressure increase, an interesting experimental study with a sand box on a shaking table was conducted and the effects of acceleration level, frequency and relative density on liquefaction potential were investigated. It is not clear how the authors obtained their Fig. 12 showing the reduction of friction angle with increasing acceleration level.

Sy and Campanella in their Paper 3.39 propose an alternative method of SPT energy determination based on measurement of both force and acceleration time histories. The measured force and integral of acceleration (velocity) wave traces provide considerable insight into the dynamics of the SPT and allow a more fundamental approach to calculating transferred energy in the SPT drill rods. The proposed force-velocity integration method of calculating SPT energy avoids several shortcomings in the existing method based on force measurement alone. The SPT energies calculated by both methods from field measurements at a research test site are compared. The results show that the existing force integration method of calculating SPT energy gives only approximate values, and also that the stress wave speed correction factor, K_c, in ASTM D4633-86 is unnecessary in calculating energy.

The last paper on field-based liquefaction assessment, Paper 3.55 by Teparaksa, extends Shibata and Teparaksa's (1988) proposed CPT based method for evaluation of liquefaction potential of soils, based on field performance of sites during past earthquakes. The applications of this empirical procedure, to sites which did and did not liquefy during the Nihonkai-Chubu earthquake of 1983 in Japan and to several sites before and after ground improvement are illustrated.

Laboratory-based Approaches

The first of four papers in this subcategory, Paper 3.8 by Tokimatsu, Kuwayama and Tamura, presents a practical procedure for evaluating liquefaction potential of sands and silty sands using shear wave velocity as the soil index. The authors review their previous laboratory-developed correlations of cyclic stress ratio causing liquefaction and normalized shear wave velocity, and apply the procedure to 17 sites in Niigata City for which field performances during the 1964 Niigata earthquake are known. The calculated behaviors are consistent with field observations. The field verification of the proposed simplified method is based on field measurements of shear wave velocity by the Rayleigh Wave method, similar to Stokoe's Spectral Analysis of Surface Waves method (Stokoe and Nazarian, 1984).

Paper 3.16 by Tanaka, Kokusho, Kudo and Yoshida presents results of undrained cyclic triaxial tests on undisturbed gravelly soils obtained by an in-situ freezing sampling technique from four sites in Japan. The field investigations included SPT, CPT and the so-called Large Penetration Test (LPT) profiles at the sites. Based on the results of this study and other available results, the authors propose a correlation between the laboratory-derived dynamic resistance and normalized LPT blow count. The dynamic resistance is defined as the cyclic stress ratio required to reach a double axial strain amplitude of 2% or 2.5% in 20 loading cycles. It would be useful if the authors provide a description of the LPT method.

Paper 3.38 by Cao and Law extends their energy approach for liquefaction failure of sandy soils to sandy and clayey silts. The criterion for liquefaction potential assessment is expressed in terms of the earthquake magnitude, hypocentral distance, and SPT blow count. Laboratory cyclic triaxial tests were conducted on reconstituted silt samples with varying amounts of sand and clay sized particles. The laboratory results were used to extend the original criterion for sand to silt, sandy silt and clayey silt. The criterion proposed, however, does not explicitly account for the influence of depth or confining pressure on liquefaction resistance.

Paper 3.62 by Pillai proposes the critical state concept to reinterpret Seed's correction factors for sloping ground due to initial static shear, K_α, and for depth due to high confining pressure, K_σ. The author uses published laboratory test data to relate K_α to state parameter instead of relative density. The state parameter, ψ, is a fundamental large strain soil property which incorporates the effects of both void ratio (or density) and confining stress. The author also suggests that K_σ is only applicable to dilative soils, for which $\psi<0$. It should be noted, however, that although the state parameter is a more fundamental parameter, it is not easy to measure readily in practice.

Dynamic Analyses

The five papers in this subcategory deal with dynamic analysis for liquefaction evaluation. Paper 3.10 by Fujii presents an interesting comparison of total and effective stress liquefaction analyses for a high rise building in Niigata City. In the total stress approach, dynamic analysis of a two-dimensional soil-structure model was performed and the cyclic strengths from laboratory tests were compared to earthquake-induced cyclic shear stresses. Both one-dimensional and two-dimensional effective stress analyses were conducted using the computer program DIANA. The liquefaction behaviors observed in the effective stress analyses are in general agreement with the results of the total stress analysis, but the effective stress analysis offers more insight into pore pressure development and reduction in effective stress during earthquake loading.

Paper 3.11 by Irfan presents a liquefaction potential assessment of the foundation for a major dam in Pakistan's Indus River. The procedure uses two-dimensional static and dynamic finite element analyses to calculate the cyclic shear stresses due to the design earthquake. These are compared to cyclic shear resistances obtained from Seed's SPT liquefaction correlations. Remedial measures to improve the factor of safety against liquefaction and to limit deformation to acceptable levels are described. The liquefaction procedure employed in this paper is the total stress approach widely used in practice.

Shiomi, Shigeno, Sugumoto and Suzuki in their Paper 3.34 present a comprehensive analysis for a typical 19 story apartment building in Tokyo supported on piles founded in soft liquefiable soils. The two-dimensional pile-soil-structure model was analyzed using a dynamic effective stress analysis code, MuDIAN. The computed vibration modes and the building, pile and ground responses due to three input earthquake motions are presented.

Paper 3.45 by Morio presents a constitutive relation for sand which simulates the inelastic soil behavior under multi-directional cyclic shear stresses. The proposed anisotropic hardening model is incorporated in the effective stress computer code DIANA-J which is used to analyze three cases: an undrained simple shear test element, a one-dimensional level ground liquefaction problem, and two-dimensional simulation of a centrifuge test of an embankment.

The last paper in this subcategory, Paper 3.68 by Zhang and Xie, presents a semi-analytical iteration algorithm to calculate seismic porewater pressure using the pore pressure generation-dissipation model presented in their companion Paper 3.67. The algorithm updates the permeability and volume strain changes during earthquake. An example problem consisting of a one-dimensional sand layer is analyzed.

Mathematical Approaches

Paper 3.23 by Du and Zhang presents a mathematical approach to liquefaction assessment using an optimum seeking method based on Fibonnacci search procedure. A data base of 40 sites for which liquefaction performances were known was compiled. The first 20 case histories were used in the optimization analysis in which five influencing factors were optimized, and the results were used to "predict" the performances of the other 20 cases. The success rate was 95%. The approach is flexible in that it can allow many more factors to be considered, but does not appear as "simple and practical" as the authors indicate.

Paper 3.56 by Zhang and Hu presents another mathematical method of liquefaction evaluation based on fuzzy theory. Factors affecting liquefaction are considered in a factor tree approach with weightings applied to the factors. The multistage multifactorial method is used to analyze a data base of 38 liquefaction case histories and the results suggest a high "prediction" success rate.

RESIDUAL STRENGTH

The only paper in this category is Paper 3.49 by Fei and Lu. The authors used a laboratory dynamic/static ring shear device to study the effects of fines content on residual shear strength of silt. Correlations between residual strength and fines content are presented. The laboratory results confirm field evidence from Tangshan earthquake that residual strength of silt increases with increase in fines content. The authors, however, did not clearly define their "fines content, P_c".

PERMANENT DEFORMATION

Settlements

The first of 3 papers in this subcategory, Paper 3.2 by Xie and Shi, proposes an analytical approach to calculate earthquake-induced building settlement using a "softening model". The approach was used to calculate settlements for 33 case histories in China for which the authors claimed to have obtained good correspondence with the observed settlements.

Paper 3.9 by Yasuhara, Hyodo, Konami and Hirao proposes a simplified procedure for calculating earthquake-induced settlements in clay due to dissipation of excess pore pressure generated during cyclic loading. The procedure is based on the results of cyclic triaxial tests combined with consolidation theory, and involves the determination of cyclic induced excess pore pressure, followed by calculation of post cyclic volumetric strain. Laboratory cyclic triaxial tests on reconstituted Ariake clay from Japan are used to illustrate the proposed method.

Paper 3.35 by Matsuda, Ohara and Hoshiyama presents another procedure for calculating earthquake-induced settlement in clay layers due to excess pore pressure dissipation. The procedure is based on the results of strain controlled cyclic simple shear tests and requires the conversion of irregular strain time history at different depths to equivalent number of uniform strain cycles for an equivalent uniform strain amplitude. The method is applied to two case histories and the results illustrate that seismic-induced settlement is affected by the characteristics of the ground motion.

Horizontal Displacements

Paper 3.28 by Baziar and Dobry proposes a laboratory-based approach for estimating liquefaction-induced horizontal deformation in silty sand. Undrained monotonic triaxial compression tests and cyclic torsional tests were conducted on very loose, contractive silty sand samples formed by the Remolded Discontinuously Wet Pluvial Soil Sample (RDWPSS) preparation method to determine steady state shear strengths. The results of monotonic and cyclic tests give similar steady state characteristics and suggest a constant ratio of steady state strength to major principal effective stress. The steady state strength is then used in a Newmark's sliding block analysis to calculate permanent horizontal displacement. The proposed procedure is applied to a well-documented lateral spread case history from Imperial Valley in Southern California, and the results of the analysis are encouraging.

The other permanent soil deformation paper, Paper 3.51 by Hamada, Yasuda and Wakamatsu, documents field observations of liquefaction-induced permanent ground displacements in Niigata City following the 1964 Niigata earthquake. Permanent displacements estimated from airphotos at two sites are presented, together with soils information obtained from site investigations. The study revealed that the gradient of the ground surface, the gradient of the bottom of the liquefied layer and the thickness of the liquefied layer were the main factors affecting the magnitude of the horizontal displacements.

REMEDIAL MEASURES

The first of 3 papers in this final category, Paper 3.5 by Xu, presents a theoretical formulation for analysis of gravel drains installed in liquefiable sand deposits. The analysis takes into account both vertical and radial drainages. Some typical results are illustrated and practical charts are presented as an aid in design.

Paper 3.21 by Qiu, Fan, Fan and Shi presents a case history at an industrial site in China in which a modified ground improvement technique, the so-called twice dynamic consolidation method, was used to treat liquefiable deep sand deposits. The treatment was carried out in two steps: the conventional dynamic consolidation, and after a time period, a top layer of the compacted soil was excavated and the second stage dynamic consolidation conducted. It was postulated that after the first stage tamping, the permeability of the soil was reduced substantially so that the second stage tamping could be performed in the dry, even below the groundwater table. The liquefaction potential evaluations were based on both field SPT and laboratory triaxial test data.

The final paper, Paper 3.24 by Ono, Ito, Nagajima and Oishi, describes the development of an auger/compaction-rod type machine for gravel drain installation. The equipment produces low levels of vibration and noise, and practically no disturbance to surrounding ground during installation, yet it appears to compact adjacent soils. Large scale laboratory model tests were conducted to investigate the various factors affecting the compaction effort of the machine. It is not clear what mechanism causes the surrounding soils to be improved if the technique, as the authors claimed, produces little vibration and no horizontal displacement of the soil.

SUMMARY AND CONCLUSIONS

The title of this session, "Deformation and Liquefaction of Sands, Silts, Gravels and Clays", is very appropriate. The 43 papers in the session cover the broad subject of liquefaction, from understanding the mechanics of liquefaction to remedial measures used to mitigate the liquefaction hazard. The papers deal not only with the liquefaction phenomenon, but also with deformation, of sands, silts, gravels and clays.

Our knowledge and understanding of the liquefaction phenomenon are increased by well-documented field observations, carefully controlled laboratory experiments, and development of realistic soil models, as presented in several papers in this session. The use of in-situ freezing method to obtain undisturbed samples, such as that used by Nishio and Tamaoki (3.19) and also by Tanaka, Kokusho, Kudo and Yoshida (3.16) to sample gravelly soils, should be encouraged.

The many papers on the analysis and evaluation of liquefaction potential show that current practice relies heavily on field-based empirical approaches or on laboratory-derived correlations applied to field test data. The Seed's simplified procedure based on SPT continues to be the most widely used method in practice. The SPT, however, is far from "standard", and it is well known that many factors influence the SPT blow count, the most significant factor being the amount of hammer energy delivered into the drill rods. Sy and Campanella (3.39) have shown that the existing method of determining energy using only force measurement is approximate, and that a more rational method based on both force and velocity measurements should be adopted.

Liquefaction correlations based on other in-situ tests show promising results. Reyna and Chameau's (3.13) DMT correlations and Teparaksa's (3.55) CPT correlations are encouraging, and both can be improved as more data become available. For gravelly soils, the LPT used by Tanaka, Kokusho, Kudo and Yoshida (3.16) may be a useful approach. Liquefaction potential evaluation based on shear wave velocity, such as that presented in Tokimatsu, Kuwayama and Tamura (3.8), shows considerable promise, but field verifications should be continued.

The practical approach undertaken by Martin, Tsai and Arulmoli (3.18) for liquefaction potential evaluation and site remediation at a large housing development is worth noting.

Dynamic analysis in practice continues to be dominated by the total stress approach, as illustrated by several papers in this session. Effective stress analysis, such as that carried out by Fujii (3.10), offers more insight into the development of excess pore pressure and the progress of liquefaction. However, the constitutive relations for soils employed in effective stress analyses are more complex and require more input parameters, some of which are not readily obtained or measured in practice. More research into this area is warranted.

On the topic of residual strength, the results of the laboratory tests conducted by Fei and Lu (3.49) on silt to show the effects of fines content are enlightening.

The laboratory-based approach proposed by Baziar and Dobry (3.28) for calculating liquefaction-induced permanent horizontal displacement in silty sand is a simple and rational approach. The extension of their simplified procedure to sand would be valuable.

Finally, on remedial measures, the practical charts presented by Xu (3.5) may be useful for preliminary design of gravel drains.

The papers in this session should advance our state of the knowledge on liquefaction and permanent deformation of soils. However, more work remains to be done to increase our understanding of this complex subject and to provide sound and practical approaches to liquefaction evaluation and mitigation.

ISSUES FOR DISCUSSION

The reporters present the following comments and questions for discussion. Early submission of written discussions is encouraged. Please come prepared to discuss some of the following issues or others raised in this General Report.

1. Laboratory tests have contributed significantly to our basic understanding of the mechanism of liquefaction and the behavior of different materials at various densities and effective stresses. These tests have traditionally been performed on reconstituted soil samples. Isn't it about time that we concentrate efforts on testing quality undisturbed samples, such as those that can be retrieved by in-situ freezing technique?

2. For evaluation of liquefaction potential, is the Seed's simplified SPT-based procedure adequate, if we can somehow measure reliably the transferred energy in the drill rods for every test? Is there a need for DMT-based liquefaction correlations? The CPT gives reliable and continuous penetration resistance which surely must be a better measurement than the SPT blow count. Should we not encourage that more work be done to increase the CPT data base for liquefaction correlations?

3. The in-situ shear wave velocity can be obtained from non-destructive surface wave testing technique or from conventional crosshole or downhole methods. The use of shear wave velocity for liquefaction potential evaluation purports to show considerable promise, or does it? The shear wave velocity approach appears to apply to all soil types, and it seems that fines content has little or no effect on the shear wave velocity-based correlations. However, it is well known that fines content has a significant influence on liquefaction resistance based on SPT or CPT penetration resistance. These conclusions seem incompatible!

4. The current approach in determining residual strength is to use either the Seed's field-based residual strength correlation with SPT blow count or Castro's laboratory-derived steady state strength. Recent laboratory tests have suggested that the residual or steady state strength determined from undrained laboratory tests is not a unique parameter, but is dependent on the stress path followed to failure, e.g. compression versus extension loadings. This could explain the often noted disparity between values obtained by the above field-based and laboratory-based approaches. The suggested use of a constant ratio of steady state strength to major principal effective stress, similar to the S_u/p' concept, could be further investigated and extended to field-based residual strength correlations. Is this a more fundamental approach? How else could we incorporate residual strength for analysis of sloping ground?

5. Field observations of liquefaction-induced permanent deformations or lateral spreading have been well documented in recent years. With the available body of knowledge, is there a simple practical procedure for predicting such deformations reliably?

6. What are we doing to verify our models for predicting partial liquefaction and subsequent deformations?

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