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General Report — Session 4: Soil Amplification; Liquefaction and Ground Failures; Seismic Studies of Loma Prieta, Northridge, Kobe, and Other Recent Earthquakes; Spatial Liquefaction

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SOIL AMPLIFICATION; LIQUEFACTION AND GROUND FAILURES; SEISMIC STUDIES OF LOMA PRIETA, NORTHRIDGE, KOBE, AND OTHER RECENT EARTHQUAKES; SPATIAL LIQUEFACTION

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INTRODUCTION

There were 40 papers submitted to this session, with 114 authors from 13 countries: 48 from Japan, 35 from the United States, 4 each from India, Iran, and Italy, 3 each from China, Greece, Taiwan, and Mexico, 2 each from Singapore, Canada, and Russia, and 1 from Colombia.

The papers were primarily classified into 9 general topics. Although some papers refer to more than one topic, this classification was necessary for both reporting purposes and distribution of papers among the General Reporter and the Co-Reporters for their evaluation. The topics into which the papers are classified for purposes of this report are presented in Table 1. An alternate classification of papers is also noted in the table, in order to facilitate identification of all papers containing contributions to any specific topic.

Table 1 – Classification of Papers by Topic

General Topic	Paper Number (xx of No. 4.xx) Primary Classification	Paper Number (xx of No. 4.xx) Alternate Classification
Soil amplification	13 26	38
Analysis of liquefaction and liquefaction effects	05 07 16 17 21 27 31 36 58	06 10 11 25 30 34 38 44 47 53
Probabilistic assessment of liquefaction and its effects	18 23 24 25	
Evaluation of liquefaction potential of sites	09 20 22 32 59	08 16 21 55
Characterization of particular soil liquefiability	04 06 28 37 55	12
Liquefaction effect on structures	08 34 44 57	21
Liquefaction mitigation	10 19 42	
Seismic studies of recent earthquakes	11 12 30 38 39 47 53	13 34 42 44 56 57
Spatial liquefaction	56	22 24 32

SOIL AMPLIFICATION

Two papers refer to soil amplification specific to soil and rock conditions in large urban regions: New York City, NY where no strong earthquake record is available, and Medellin, Colombia where an extensive accelerograph network and recent earthquakes occurrence provided useful data. A third paper (No. **4.38**, reviewed under the topic of "Seismic Studies of Recent Earthquakes") refers to a much smaller area in Kobe, Japan where differences in the degree of consolidation of a deep soft clay layer were credited to explain significant differences in liquefaction damage of artificial islands.

Paper No. **4.13** by **Estada**. Accelerographs were installed at 23 sites considering topographical and geotechnical conditions in Medellin in Colombia. In addition another instrument was installed on bedrock. Recorded earthquakes by the accelerograph network showed deep differences in seismic response among several zones in the city. The author compared amplification with average shear wave velocity of surface soil and impedance ratio, then concluded that the impedance ratio and internal soil damping ratio play an important role on the amplification effects. Moreover, it was found that the criterion of the average shear velocity of the top 100 ft is not appropriate to represent seismic response. It is desired to discuss the definition of bedrock because appropriate shear wave velocity for bedrock has not been unified in the world. Adaptability of seismic response analyses in Medellin is desired to be discussed also.

Paper No. **4.26** by **Nikolaou et al.** Soil amplification effects in New York City may be significant because of the presence of soft soil deposits and hard bedrock. Then amplification studies in New York City were carried out by one-dimensional seismic response analyses for ten typical soil profiles under different hazard levels and different assumptions regarding the stiffness characteristics. It was shown that although seismic hazards in the area is only moderate, significant soil effects can be generated and lead to large amplification. The analyzed results were compared with the design spectra of the 1995 NYC Seismic Code, and it was concluded that the Code provides conservative design parameters but unconservative amplification values. It is desired to discuss the effect of existence of buildings on the amplification, because clustered skyscrapers may affect the seismic response on the ground surface in downtown area in New York City.

ANALYSIS OF LIQUEFACTION AND LIQUEFACTION EFFCTS

A total of 9 papers related to the analysis of liquefaction and of post-liquefaction behavior of soils were reviewed. Three of these papers used the finite element method (FEM) and two others were based on analyses either by the Distinct Element or the finite difference method (FDM). There were two papers reporting results of laboratory testing either by centrifuge or shake table, whereas the two remaining papers used field data to train a neural network or to improve the definition of the factor of safety to determine whether or not a deposit will liquefy. Detailed summaries of these papers follow.

Elgamal and Yang (paper No. **4.17**) developed a new constitutive model, which has been integrated in an effective stress fully coupled two-phase finite elements code (CYCLIC). The model is capable of reproducing the large post-liquefaction shear strain accumulation with the introduction of a perfectly plastic zone into a multi yield surface stress-space framework, as well as the possible regain in shear strength and stiffness because of the dilative soil behavior. CYCLIC has been calibrated with laboratory and centrifuge test results and was specifically used in this paper to study the dynamic behavior of a waterfront embankment.

Luan and Wang (paper No. **4.31**) also used the finite elements technique in combination with the two-dimensional Biot's theory of dynamic consolidation to model pore pressure development in an elastic or elasto-plastic seabed subjected to wave loading. The authors incorporated an iterative time integration procedure to predict the dynamic response of the seabed. The numerical solution presented by the authors compares favorably well with analytical solutions previously reported.

The finite elements program NISA II was used by **Hosseini and Nateghi** (paper No. **4.07**) to study the mechanism of crack development starting in sand lenses embedded in a stiff clay, due to liquefaction. After applying the earthquake loads and using the Drucker-Prager model, the program yields the crack development path, which is in good agreement with values previously reported in the literature.

A three-dimensional Distinct Element Model (DEM) was developed and used by **Ravichandran and Meguro** (paper No. **4.58**) to simulate liquefaction in hollow cylinder torsional tests, as well as to simulate the occurrence of sand boils. The DEM method treats granular soils as discrete particles as opposed to the finite elements method, which treats the soil as a continuous medium. The procedure appears to be capable of simulating the shear displacement, excess pore water pressure, void ratio and shear stress time histories, although no comparisons with actual test data were given.

Beaty and Byrne (paper No. **4.27**) compared the liquefaction-related behavior of the Upper and Lower San Fernando dams during and immediately after the 1971 San Fernando earthquake. They concluded that even though the materials in both dams are alike and have comparable blow counts the dissimilar behavior of the two dams could be attributed to the difference in the driving stress in the upstream shell. FDM and limit equilibrium analyses conducted by the authors indicated minimum post-liquefaction strength values between 14 to 24 kPa, with lower localized values in particular during sliding of the lower dam. They concluded that stability evaluations based on undrained laboratory tests may be unconservative because of additional complex mechanisms occupying in soils that can greatly reduce their residual strength.

Other computer programs used in the liquefaction effect evaluation by authors that submitted papers to this session were: LIQCA3D and LIQCA2D – two-dimensional and three-dimensional coupled dynamic analysis using FEM for spatial discretization of the equilibrium equation and FDM for spatial discretization of the pore-water pressure in continuity equation (paper No. **4.10**); FLIP – post liquefaction ground settlement evaluation (papers Nos. **4.11, 4.42,** and **4.44**); LASPRED-1D – Newmark type lateral displacement evaluation (paper No. **4.53**); SUMDES – nonlinear dynamic effective stress site response analysis (paper No. **4.30**); SHAKE – equivalent linear dynamic total stress analysis (papers Nos. **4.26**, **4.30**, and **4.38**). A critical state model was used in the study presented in paper No. **4.06**. The method ALID is proposed in paper No. **4.34** for the analysis of liquefaction induced deformation.

The energy method to define the liquefaction potential of soils when subjected to dynamic loading was examined by **Dief et al.** (paper No. **4.16**) through a series of dynamic centrifuge tests on several sands. The dissipated energy per unit volume in a soil deposit modeled in the centrifuge was determined from the shear stress-strain time histories calculated from recorded horizontal accelerations and lateral displacements at different depths within the prototype. Centrifuge test results indicated that the energy per unit volume increase was related to the pore pressure development, with the major contribution to the energy per unit volume occurring at the time of the higher pore pressure build up. These results also showed that the soil liquefied at approximately the same depth where the dissipated energy, calculated from the stress-strain loops, exceeded the resistance in terms of the amount of energy required for liquefaction, as determined from torsional shear tests.

Sinusoidal shake table tests allowed **Kobayashi et al.** (paper No. **4.21**) to evaluate the reduction coefficient of the horizontal subgrade reaction during liquefaction. The horizontal subgrade reaction was measured with a piston penetrating the side of the soil container before and after liquefaction. The authors found that the reduction coefficient of low shear strength sands drastically decreases when the liquefaction resistance factor (ratio of cyclic stress required to cause 7.5% double amplitude shear strain in 20 cycles, over the shear stress ratio in 20 cycles of loading) is near unity. The coefficient slowly decreases when the resistance facto is less than one. They also determined that the subgrade reaction decreased as the shear strain increased, while it increased with higher cyclic velocity.

Centrifuge test results were also reported in papers Nos. **4.19**, **4.34**, **4.38**, and **4.53** (presented under different topics, see Table 1).

An artificial neural network was trained by **Kurup and Dudani** (paper No. **4.36**) with ninety-six data sets to predict the liquefaction potential from CPT data. All data sets included input parameters affecting liquefaction such as cone resistance, total vertical stress, effective vertical stress, earthquake magnitude, maximum horizontal acceleration at the ground surface, mean grain size D_{50} and seismic shear stress-ratio. The neural network model was tested and validated with eighty-two data sets yielding a 96% success rate in predicting liquefaction. The procedure is expedient and offers the potential for improvement as more data become available.

The application of an artificial neural network model for evaluating soil liquefaction potential using shear wave velocity measurements is presented in paper No. **4.25.**

Olson and Stark (paper No. **4.05**) applied the liquefaction analysis procedure previously developed by the first author to the case history of Lower San Fernando Dam failure. Based on back calculation of well documented liquefaction flow failures, this method of analysis addresses all three main steps of a complete evaluation of liquefaction susceptibility of the ground subjected to a static shear stress: flow failure susceptibility; liquefaction triggering; and post-triggering flow failure. For this purpose, simple relations for estimation of yield strength ratio and liquefied strength ratio from SPT and CPT data were developed. Although this study does not represent a "Class A" prediction and, therefore, can not fully validate the proposed procedure, it demonstrates a good agreement between analysis results and the actual behavior of the Lower San Fernando Dam.

PROBABILISTIC ASSESSMENT OF LIQUEFACTION AND ITS EFFECTS

Deterministic approach has been widely used in current design methods for liquefaction problems. However, it is desired to introduce probabilistic evaluation methods also in future design methods. The probabilistic approach will be able to be applied in several processes of the design for liquefaction problems: estimation of the occurrence of liquefaction, evaluation of liquefaction-induced ground flow, evaluation of liquefaction-induced deformation of structures, design of countermeasures against liquefaction and microzonation for liquefaction potential. Two papers (Nos. **4.23** and **4.25**) deal with probabilistic evaluation methods for liquefaction potential based on SPT, CPT and V_s. In the third (No. **4.18**) and the fourth (No. **4.24**) papers, probabilistic approach was applied for liquefaction-induced lateral spread evaluation and microzoning, respectively.

Paper No. **4.18** by **Rauch**. In a liquefaction-induced lateral spread of sloping ground, horizontal displacements on the ground surface vary with relative position on the slide mass. Appropriate probability density functions for modeling the variation in horizontal displacements were studied using 29 case studies of lateral spreading which were induced in Japan and California. In the study, the quality of fit between the measured displacements and normal, lognomal and gamma distributions were evaluated using statistical goodness-of fit tests. The results showed that the gamma distribution provides a good representation of the variation in displacement magnitudes across a slide area. It is desired to discuss on the effect of the length of the slide area on the adaptability of gamma distribution, because distribution pattern of displacements on a slope may be affected by the length of the slope.

Paper No. **4.23** by **Juang et al.** Probabilistic evaluation methods for liquefaction potential based on SPT and CPT were studied. In both evaluations, logistic regression and Bayesian techniques were applied. Database for liquefied and non-liquefied cases were used for the analyses. The analyses showed Bayesian approach yields more conservative results than does the logistic regression approach, although results from the two approaches are quite comparable. SPT and CPT deterministic curves (boundary curves between liquefied and non-liquefied data) coincided with the 30% and 50% probability curves, respectively. Procedure for risk-based liquefaction potential evaluation was also presented. It is desired to discuss how to combine with the probability of other factors such as design acceleration.

Paper No. **4.24** by **Rodriguez-Marek.** A technique to estimate the probability of liquefaction over arbitrary large areas was proposed. In the method, the area of interest is meshed forming a grid of individual cells, for which the probability of liquefaction is estimated. The probability of liquefaction for a given percentage of total area is then computed as a system reliability problem. A sample problem was solved for illustration purpose, and it was concluded that "point" probabilistic liquefaction models alone are inapt to compute_the spatial extent of liquefaction. Discussion is desired whether this kind of approach is useful by neglecting geomorphological conditions, because liquefaction potential is strongly correlated with geomorphological condition (e.g. TC4, ISSMFE, 1993).

Paper No. **4.25** by **Juang et al.** Vs-based simplified procedure for evaluating liquefaction potential provides a promising alternative, and/or supplement, to penetration-based procedures. Three probability-based models and one artificial neural network model for evaluating liquefaction potential using Vs were compared with the deterministic curve (relationship between Vs and cyclic stress ratio). The probability models were developed using logistic regression and Bayesian techniques applied to the same case history data used to develop the deterministic relationship. Results showed that the deterministic curve is characterized with a probability of about 30 % in the logistic regression and Bayesian models. This value was almost same for SPT-based approach shown in Paper No. 4.23. It is desired to discuss why the probability of the deterministic curve for Vs-based evaluation is almost same as the deterministic curves for SPT-based evaluation. In general understanding, SPT-based evaluation method is most accurate and Vs-based evaluation method is most inaccurate.

EVALUATION OF LIQUEFACTION POTENTIAL OF SITES

The regional and local geology, groundwater depths, composition, and density and stress state of the deposits are among the main factors that determine the liquefaction potential of a site. Methods for evaluating the liquefaction potential of a site are therefore designed to account for the above factors in various details. Considering the difficulty of obtaining sufficient, good quality, undisturbed soil samples for a given project in-situ field tests are preferred for determination of liquefaction potential. Moreover, the field tests are considered to inherently embody the effect of various above-mentioned factors. However, corrections are often used to emphasize the importance one or the other factor. The paper by Hosseinii compares two of these field tests, the SPT and CPT, for prediction of liquefaction potential. Castelli et al. utilize data from CPT to develop liquefaction risk microzonation map of City of Trapani. On the other hand, Mansoor et al. and Dayal and Jain utilize data from SPT tests to assess liquefaction risk in Aqaba region of Jordan and a specific site in Northeast India, respectively. Johnsen et al. study the differences in various SPT rigs and its consequences through the energy transfer efficiencies. Detailed discusion of each of these paper follows.

Hosseini (paper No. **4.09**) assesses the liquefaction potential of a site using both the SPT data and the CPT data. Safety factors against liquefaction calculated using SPT data corrected for fines content are directly compared with those calculated using CPT data corrected for soil behavior index I_c. Poor correlation is obtained between the safety factors from the two data. Hosseini's findings are in contrast with the work by Youd and Gilstrap (1999), who reported a better correlation between safety factors from SPT and CPT data. Hosseini attributes this difference in findings to the soil type assessed in the two studies. While Hosseini's work deals with a site consisting of fine silty sands to sandy silts, Youd and Gilstrap's work dealt with a site containing clean sand to silty sands. However, the question that remains to be answered is which data, SPT data or CPT data gives a reliable assessment of a site's liquefaction potential. CPT data is widely considered to be of higher quality, however, does that truly mean that liquefaction potential predicted with this data is more reliable?

Johnsen et al. (paper No. **4.20**) have measured the energy transfer efficiencies of 16 SPT rigs, including five automatic safety hammers, five wire line safety hammers, two rope and cathead safety hammers and four donut hammers. The energy transfer efficiencies varied from 31 to 77 percent, with the automatic hammers having the highest and the donut hammers with rope and cathead mechanism having the lowest efficiency. The wireline and rope and cathead hammers also had larger variability than their counterparts. They have correctly concluded that transfer energy corrections should be applied to SPT data prior to its use in both dynamic and static analyses. They have also found that a Pile Driving Analyzer (PDA) could be used for analysis of energy transfer efficiencies.

Castelli et al. (paper No. **4.22**) have constructed a liquefaction susceptibility microzonation map of the City of Trapani (Italy) using CPT data and method proposed by Robertson and Wride (1997). The city of Trapani is sited on deposits that are described as layers of calcarenitic and silty clay or silty sand. Based upon CPT data the city of Trapani is divided into 13 sub-regions. Liquefaction potential index P_L is computed at various locations using a procedure attributed to Iwasaki et al. (1978). Example profiles of liquefaction potential index with depth are given for CPT No. 16. Representative liquefaction potential indices are also given for each of the 13 sub-regions. As a result a microzonation map of liquefaction risk for city of Trapani is developed.

Mansoor et al. (paper No. **4.32**) have described the geological and geotechnical factors that are associated with the potential for liquefaction at sites in Aqaba region of Jordan. Through various field-mapping techniques they have detailed the tectonic activities in this region. They have then assessed the liquefaction potential at various sites in this region based upon corrected SPT data and method developed by Seed and coworkers. The liquefaction potential is calculated for three peak ground accelerations. The results of liquefaction are superimposed upon the map of Aqaba region to highlight the potential consequence liquefaction in this region. This data may be used to develop a microzonation liquefaction risk map of Aqaba region in Jordan.

Dayal and Jain (paper No. **4.59**) have evaluated the liquefaction susceptibility of a site located in the alluvial plain of river Brahmaputra in India's northeast. They have also evaluated the consequences of liquefaction on the behavior of bridge foundations and embankments to be constructed at this site. Liquefaction potential is evaluated using corrected SPT data and the procedure developed by Seed et al. 1983. The analysis is performed for two levels of peak ground acceleration, to assess the liquefaction potential for both functional and safety criteria. Under functional criteria, no liquefaction is expected at the site. Under safety consideration, liquefaction is expected at various depths under both the foundations as well as the embankments. Consequently, settlements and stability of the structures are analyzed assuming appropriate residual strengths of the liquefied strata.

CHARACTERIZATION OF PARTICULAR SOIL LIQUEFIABILITY

Three of five papers classified under this topic investigate the liquefaction potential of artificially prepared mixtures of sand with various proportions of fines. Although all three studies are essentially experimental, they use different approaches for evaluation of liquefaction parameters: dynamic triaxial test, monotonic direct shear, and numerical modeling. The main studied parameter is also different: liquefaction triggering, post-liquefaction settlement, and steady state (residual) strength. Two other papers use classic approach (cyclic triaxial, SPT) to determine liquefaction susceptibility of cohesive materials that generally are considered non-liquefiable under usual circumstances.

The work by **Thevanayagam et al.** (paper No. **4.28**) is an expe-rimental study of pore pressure generation during dynamic loading and post-liquefaction densification characteristics of sand/silt mixtures. The purpose of this study was to better understand the effect of fines on post-liquefaction settlement of silty soils and also to help optimize the design of soil improvement techniques based on densification. The conclusion was that the lower permeability and the smaller coefficient of consolidation of silty sands as compared to clean sands require closer spacing of dynamic compaction or stone column grids, or supplementary wick drains to expedite dissipation of pore pressure developed during ground improvement operation.

In their paper (No. **4.37**), **Wang and Sassa** describe the results of testing artificial mixtures of sand with up to 30% loess in a direct shear apparatus. The ring-shear device allows for large displacements in the shear zone, typically of the order of meters. Both the peak shear strength and the steady state strength decreased significantly with increasing silt (loess) content at a particular void ratio. It was also observed that a higher loess content in the mixture slowed or even prevented dissipation of excess pore pressure; the authors consider this an explanation of large deformations experienced by liquefied deposits of sand with fines, where high excess pore pressure exist for long time. However, it is the reviewer's opinion that migration of water from liquefied zones with high permeability towards zones critical for stability, and the corresponding redistribution of the excess pore pressure, can also generate large post-earthquake deformations.

Andrianopoulos et al. (paper No. **4.06**) present an interesting indirect approach to assess the effect of fines on liquefaction potential. Based on statistical analysis of triaxial test results on sand samples with various fines amount it was determined the effect of fines on the Critical State (CS) line. The corresponding findings were subsequently used within a CS constitutive model to simulate cyclic undrained triaxial tests. The simulations showed that increasing amount of fines increases the resistance against liquefaction at relatively low confining effective stresses, less than approximately 86 kPa; the effect of fines content is opposite at relatively high effective stresses. The study did not address the effect of fines plasticity; it is also apparent that the constitutive model was calibrated based on reconstituted samples, so that the effect of fabric could not be considered.

Anubhav and Rao (paper No. **4.55**) tested for liquefiability an Indian cohesive soil deposit with relatively high plasticity (LL = 34, PI = 16) and clay fraction content (28%), which generally is considered non-liquefiable. Good agreement was found between the cyclic stress ratio as determined by cyclic triaxial tests and its indirect evaluation using SPT corrected for fines content The soil deposit was characterized as highly liquefiable, but only if a strong earthquake (magnitude in excess of 7) occurs at less than 40 km epicentral distance. It is noted that soils with moderate of high plasticity may "liquefy" in laboratory if the criterion of 5% double amplitude axial stain is accepted, but generally do not manifest significant post-triggering-liquefaction loss of strength, so they should not be classified as liquefiable, if liquefaction means major distress.

Paper No. **4.04** by **Wang et al.** is a joint study by specialists from China, the United States, and Russia. The experimental study is looking for both similarities and differences in liquefaction behavior of loess deposits in the three countries. All deposits are sediments wind-borne in the Pleistocene epoch, but the formation material is different: in China was brought from desert, in US from glacier, and in Russia from marine deposits. Of the three types, only the Chinese loess meets the "Chinese Criteria" for liquefaction susceptibility assessment per Seed et al. (1983) or the "modified Chinese Criteria" for ASTM definition of soil properties (Perlea et al., 1999). However, in all three countries they experienced catastrophic damage during earthquakes. The conclusion of the testing program was that all three materials are liquefiable, although the Chinese loess has the highest liquefaction potential. The differences in behavior were explained by particularities in microstructure and gradation. The application in the cyclic triaxial of an actual irregular seismic loading did not allow an accurate pore pressure measurement and a questionable criterion for definition of liquefaction triggering was used.

LIQUEFACTION EFFECT ON STRUCTURES

Although the effect of liquefaction on structures should be a topic of major interest in any case histories conference, only four papers have been classified in this category. Of these, two papers only analyze actual case histories of damage to structures induced by liquefaction (Nos. **4.34** and **4.44**); another paper (No. **4.57**) studies the cause of ground cracking in vicinity of deep foundations of bridges and the fourth paper (No. **4.08**) critically apply some available methods for bridge foundation design. Readers interested in case histories of liquefaction-induced damage to pile and raft foundations are referred to a comprehensive study co-authored by one of the co-reporters (Yasuda and Berrill, 2000) which includes a detailed and critical presentation of available methods of foundation design in liquefiable soil.

The paper No. **4.34** by **Yasuda et al.** presents applications of the previously proposed method by the authors for evaluation of liquefaction-induced displacement of grounds and structures. In this method, the residual ground deformation is estimated as the difference between pre- and post-liquefaction (static) undrained deformation. In this respect, post-liquefaction variation of shear modulus was determined for sand with up to 40% fines. Evaluation of case histories of ground flow, settlement of river levees, and settlement of footings installed in centrifuge allowed the authors to perform a fair analysis of validity and limitations of the proposed simplified method.

Tanaka et al. (paper No. **4.44**) present a summary of data collected after the occurrence of the 1995 earthquake in Kobe with reference to damage due to liquefaction on quay walls and breakwaters. Most of these structures had the original soft marine clay foundation replaced with granular fill or improved with sand compaction piles. It was found that the densification of sand at shallow depth below the structure base was controlling the settlement. The horizontal displacements of quay walls and of breakwaters were significantly different, as a direct consequence of differences in pre-earthquake static loading. Difficulties in application of a numerical model (computer program FLIP) are discussed; although the overall trend of damage variation with the intensity of the seismic loading was correctly modeled, the calculated displacements were significantly lower than actually measured.

The study by **Tazoh et al.** (paper No. **4.57**) was performed to determine the significance of ground fissures observed to develop during strong earthquakes around bridge piers. Physical and numerical modeling demonstrated that the fissures were due to tensile stresses generated by ground movement toward the river. A practical conclusion was that the damage to structures near rivers or sea banks was mainly caused by a decrease in the bearing capacity of the ground in front of the foundation, toward the river or sea. Mitigation of the damage can effectively be done by stabilization of the ground in front of the foundation, combined with strengthening of the foundation itself to compensate the potential loss of lateral bearing capacity of foundation soil.

Hosseini (paper No. **4.08**) applies the method recommended by K. Tokida to assess the liquefaction potential of a large span prestressed concrete bridge. The liquefaction potential of the site was evaluated using a site specific methodology based on a combination of AASHTO, Japan Road Association, and Seed-Idriss methods. Although some layers were found liquefiable under the design earthquake, the minor anticipated damage did not justify special design considerations. However, reduction factors were applied to the calculated bearing capacity of liquefiable layers. The paper does not present in sufficient detail the criteria leading to the conclusion that special anti-seismic measures are not necessary.

LIQUEFACTION MITIGATION

Of the three papers classified under this topic, one (No. **4.10**) discuss the effect of a steel pile ring under a petroleum tank for liquefaction hazard mitigation. The other two papers (Nos. **4.19** and **4.42**) deal with the mechanics of soil improvement by compacted sand columns.

Paper No. **4.10** by **Yashima et al.** In this paper, the authors perform numerical analyses to evaluate lateral and vertical displacements of a petroleum tank due to the liquefaction of underlying reclaimed sands during a seismic event. Prior to evaluating possible remedial techniques for the tank, vertical settlements, horizontal displacements and excess pore pressure ratios are compared for two and three-dimensional analyses for an untreated site. Then a three-dimensional finite element analysis is performed for the tank system with a steel pile ring constructed around the perimeter of the tank. In all models, the non-linearity of the ground is simulated with a kinematic-hardening, elastoplastic model. The authors comment on the differences between the two and three-dimensional analyses and on the effectiveness of the steel pile ring in limiting settlements and lateral displacements.

Paper No. **4.19** by **Adalier and Elgamal.** Densification of loose sands (vibro-rod, vibrocompaction, etc.) has long been recognized as a method for mitigating liquefaction potential. However, there are numerous questions regarding the appropriate extent of treatment. To perform a rational ground improvement design, one has to evaluate how liquefaction of surrounding soils will impact a zone of improved soil underlying a structure or earthen embankment. In this study, the authors perform dynamic centrifuge tests to model the boundary between improved and unimproved sands subjected to strong cyclic shear strains. Two tests are performed. In the first, the relative densities of the loose and dense sands are 47% and 70%, respectively. In the second, the relative densities are 40% and 90%, respectively. Test results indicate that there are boundary effects in both the excess pore pressure ratios and in lateral strains between the loose and dense sands. As one would expect, these effects are more pronounced with a greater difference in relative densities. The results of the testing are presented in the paper.

Paper No. **4.42** by **Miwa et al.** It has been recognized and well documented in the literature, that sand compaction piles were successful in minimizing and, in some cases, preventing liquefaction damage on reclaimed lands during the 1995 Hyogoken-Nambu Earthquake. In this paper, the authors investigate three factors contributing to the sand compaction method's effectiveness for mitigating liquefaction. Those factors are (1) apparent increase in relative density, (2) increase in horizontal effective stress and (3) stabilization of microstructure. The research concentrates on two sites (Nishinomiya-hama Island and Rokko Island) with well-documented soil conditions, seismic ground motion histories and performance during the earthquake. The authors perform effective stress analyses using "FLIP". It was found that the actual behavior of the subject sites was better explained by using a combination of the increase in relative density as indicated by N-values and an increase in effective stress. The authors present a method of superposition to account for the combined soil properties of the improved sands and in-situ columns.

SEISMIC STUDIES OF RECENT EARTHQUAKES

Most of the 13 papers that refer to the effects of specific recent earthquakes (7 of which being presented below) describe and analyze the damages induced by the 1995 Hyogoken-Nambu (Kobe) earthquake (Nos. **4.11, 4.12, 4.30, 4.34, 4.38, 4.42, 4.44**, and **4.56**). Each of the other papers refers to: 1999 Armenia, Colombia earthquake (**4.13**), 1999 Chi-Chi, Taiwan earthquake (**4.39**), 1998 Adana, Turkey earthquake (**4.47**), 1995 Manzanillo, Mexico earthquake (**4.53**), and 1995 Great Hanshin, Japan earthquake (**4.57**).

Paper No. **4.11** by **Hayakawa and Matsui.** This paper presents an evaluation of measured surface subsidence at multiple reclaimed sites compared to those predicted by an available empirical method. In addition, volumetric strains and settlements were estimated using the numerical simulation program "FLIP". The first method was based on a simplified model to determine volumetric strain. The other two methods evaluated volumetric strains versus residual excess pore pressures and maximum shear strains.

Paper **4.12** by **Tanaka et al.** Sand boils were observed across sections of Rokko and Port Islands after the 1995 Hyogoken-Nambu Earthquake of 1995. Portions of these islands were reclaimed with gravelly soils. To investigate the liquefaction resistance of these in-situ soils, samples were taken by the freezing technique at locations were liquefaction had apparently not occurred. Laboratory testing was performed to obtain index and liquefaction resistance properties of these materials. Using this data, numerical analyses of both sites were performed to evaluate the maximum shear stress ratios versus liquefaction strength of the soils at various depths. The analyses indicated that current available equations are effective for determining the boundary between liquefaction and non-liquefaction of gravels based on modified SPT N-values and maximum shear stress ratios.

Paper **4.30** by **Wang et al.** Ground motions were recorded with an array of downhole accelerometers at Port Island during the main and aftershocks of the Hyogoken-Nambu Earthquake in 1995. The authors compare these recorded ground motions to those predicted by two commonly used response analysis techniques to evaluate their effectiveness. The paper outlines the assumptions made in modeling the dynamic and stress-strain characteristics of the soil profile. The ground responses predicted by a nonlinear effective stress technique (SUMDES) and an equivalent linear total stress technique (SHAKE) are compared to the actual ground motion records. The results of the equivalent linear total stress analysis showed that the horizontal motion computed by SHAKE is in reasonable agreement up to liquefaction. The motion in the liquefied soil was not estimated well by this method. The nonlinear effective stress analysis showed good agreement with actual horizontal ground motions before and after liquefaction. Vertical motions predicted by both methods were in poor agreement with actual recorded motions.

Paper **4.38** by **Yamaguchi et al.** Most of the artificial islands around Kobe were reclaimed by similar landfilling methods. Although bedrock ground motions were consistent across the Kobe area, liquefaction damage differed from island to island. In this paper, the authors performed centrifuge shaking table tests to try to reproduce observation records obtained during the earthquake. The centrifuge prototype was constructed using clay and sands obtained from sampling at Rokko Island. The profile consisted of an alluvial clay layer overlain by reclaimed loose sands. The prototype was subjected to two series of tests. In the first case, the clay was consolidated under an effective stress of approximately 30% of the in-situ stress prior to shaking table testing. In the second case, the clay layer was consolidated under 100% of the effective stress prior to shaking. The results indicated that the reconstituted clays did not model the undisturbed clays at the test site accurately. In addition, the testing suggests that soft clays tend to dampen strong underlying ground motions resulting in less liquefaction in overlying loose sands. Damage appears more severe in liquefiable soils overlying stiff clays.

Paper **4.39** by **Ni and Lai.** The liquefaction-induced damage caused by the September 1999 Chi-Chi Earthquake was widespread and severe. This paper catalogs damage due to liquefaction across Yunlin, Zhangua, Nantou and Taichung Counties. In addition to the description of the damage, the authors estimated the liquefaction potential indices for these counties using six methods (Seed's, Iwasaki's, Japan Road Association, New Japan Road Association, Tokimatsu and Yoshimi, Chinese Building Code (CBC) and the Arias Intensity Method). The damage observed across these sites suggests that the CBC method is the most proper method because of its consideration of fines content.

Paper **4.47** by **Adalier.** The epicenter of the 1998 Adana Earthquake was located near the thick alluvial deposits of the Ceyhan River. The presence of loose sand-silt layers throughout the subsurface profiles resulted in a large areal distribution of liquefaction. The ground deformations associated with this liquefaction included lateral spreading, flow failures, ground fissures, sand boils, surface subsidence and slope failures. The data obtained from an extensive survey of these ground failures was compared to a small-scale model to determine possible generation mechanisms of liquefaction-based ground failures. During the field survey, attention was also paid to foundation damage of residential structures due to various ground failures due to liquefaction. The field observations and small-scale model results are presented herein.

Paper **4.53** by **Taboada-Urtuzuástegui et al.** Liquefaction-induced lateral displacements of greater than 2 meters were observed in the Container Terminal at San Pedrito in the Mexican port of Manzanillo during the October 1995 earthquake. This paper presents a prediction of lateral displacements by the Newmark sliding block method. Eleven centrifuge tests were performed to calibrate the model. The estimated lateral displacements were in good agreement with those observed on site. The authors suggest that the Newmark method is limited when estimating lateral displacements in soils that exhibit dilatant behavior. A modification to the Newmark method for use with dilatant soils is suggested.

SPATIAL LIQUEFACTION

Although several papers deal with liquefaction microzoning (see Table 1) only one was selected for review under this topic:

Wakamatsu et al. (paper **4.56**) describe the liquefaction evaluation criteria based on geomorphology, which were recently introduced in the revised Japanese Manual for Liquefaction Hazard Mapping Procedures. The evaluation criteria were verified by application to the Fukui Planes, where the actual distribution of sand boils observed in the 1948 Fukui earthquake was available. The estimated liquefaction potential was in good agreement with the observation results. We agree with the authors that such a map of liquefaction potential can be very useful for preliminary planning purposes and in identifying areas where site-specific investigations are needed.

CONCLUSIONS

Based upon the papers content and the expected conference participants' interest the following items may be considered for discussions:

With reference to "Soil Amplification":

- Definition of "rock" from soil amplification point of view and recommended values of shear wave velocity for various types of rock.
- Effect on soil amplification of deep embedment of tall buildings in large urban areas.

With reference to "Analysis of Liquefaction":

- Simplified methods to evaluate seismic displacements in liquefied ground.

With reference to "Probabilistic Assessment and Spatial Liquefaction":

- Role of geomorphological condition consideration in liquefaction hazard mapping based on probabilistic evaluation methods.

With reference to "Evaluation of Sites":

- Effect of fine contents on evaluation of liquefaction potential using SPT and CPT data.
- Developments of standards for energy transfer corrections.
- Development of criteria for the determination of effects of site liquefaction upon deformation and stability of foundations and embankments.

With reference to "Particular Soil Liquefiability":

- Use of in-situ testing for classification of soils susceptible to loss of strength due to liquefaction.
- Post-triggering liquefaction behavior of sand with fines and cohesive soils.

With reference to "Liquefaction Effect on Structures":

- Design methods of seismically loaded foundations in liquefiable soils.

With reference to "Liquefaction Mitigation":

- Extent of stabilized soil under a structure into the surrounding liquefiable soil.

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