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General Report Session 2: Model Testing in Cyclic Loading

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INTRODUCTION

Geotechnical earthquake engineering problems and similar soil dynamics problems usually involve random three directional cyclic loads, complicated stratification of soil deposits and geometry of supported structures, heterogeneity, anisotropy, and nonlinearity of soils, large degradation of soil stiffness and strength accompanied by equally large displacements and deformations, complex interaction between different soil deposits and between the foundation soil and the supported structure, etc. On the other hand, the empirical and analytical methods used in conjunction with standard field testing or standard laboratory cyclic testing on small specimens, which are currently available in engineering practice, are relatively simple and limited to ideal conditions. In most cases, such methods can provide only a rough estimate of the response of a foundation-structure system to seismic or similar cyclic loads. Consequently, large scale field and laboratory testing, testing of soil-structure models using shaking table, and centrifuge testing play an important role in the advancement of soil dynamics design methods. Such testing, however, in comparison with standard experimental and analytical soil dynamics investigations, is quite expensive. It requires special facilities with an adequate technical support and it involves team work. The affiliations of the authors in this session, as well as the number of the authors of some papers, show that such complex and expensive studies are done mainly by large corporations or large institutes in cooperation with universities.

CLASSIFICATION OF PAPERS

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SHAKING TABLE TESTS

Liquefaction

Liu and Chen in their paper "*Test on Behavior of Pile Foundation in Liquefiable Soils*" describe the results of a series of shaking table tests on the models of pile groups of different size. The investigation was done along the lines of similar investigations conducted earlier by the same authors. Smaller size models of pile groups with the piles relatively closely spaced and connected with rigid caps were installed into loose saturated sand prepared in a container on the shaking table. Due to the pile installation the sand between the piles considerably densified. After the installation each pile group model was vertically loaded, consolidated and then shaken in one horizontal direction. During shaking pore pressures and settlements were measured at different points within the sand mass, i.e., between the piles and far from the pile group. Based on the pore pressure and settlement measurements, the accelerations of shaking table, the accelerations of pile foundation and surrounding soil, and the calculated distribution of the initial effective stresses, several valuable conclusions applicable to engineering practice were derived or verified. These conclusions are: (i) in the pile group zone a loose liquefiable deposit may considerably densify during installation and lose its susceptibility to liquefaction, (ii) as a result of such densification and inability of sand between the closely spaced piles to undergo significant shear deformation, the sand between the piles may not liquefy while at the same time the sand outside in the "free field" fully liquefies, (iii) such liquefaction pattern may cause the pile group with the densified soil between the piles to behave as a deep foundation block which is "floating" in the surrounding liquified soft soil, i.e., the foundation failure in such case occurs mainly due to a large reduction in strength of the subsoil. As stated by the authors, these conclusions are in good agreement with similar previous investigations and available field evidence. Scaling relations and the effects of the boundaries of the model are not specifically discussed.

Yasuda, Nagase and Kiku in their paper "*Shaking Table Tests on Permanent Ground Displacement due to Liquefaction*" present results of 19 shaking table tests. The tests were conducted to (i) investigate patterns of the deformation of liquefied soil mass at level or slightly inclined grounds, (ii) to develop a reasonably accurate analytical procedure to predict such patterns and associated large ground displacements, and in turn (iii) to investigate, using the same analytical procedure, the countermeasures to prevent the large ground displacements caused by the liquefaction. Several typical geometries of liquefiable deposit at level or slightly sloped ground were encompassed, like for example, flat surface of the liquefiable deposit with the sloped nonliquefiable base, sloped surface of the liquefiable deposit with the sloped base, sloped surface of the liquefiable deposit with the flat base, etc. As a part of the same investigation, vane shear and cyclic torsional hollow cylinder shear tests were conducted on liquefiable sands. The vane shear tests were performed before and after the liquefaction in a sand deposited in the same shaking table box. These tests were performed separately from the main series of 19 tests and were used to develop a general relationship between sand density and the drop of the shear strength caused by liquefaction. Cyclic torsional shear tests were conducted to develop the relationship between the excess pore water pressure and the drop of the shear modulus at small cyclic strains. Based on these results describing the drop in the strength and modulus (caused by the liquefaction induced soil softening), a simple procedure for the estimation of the deformation of soil mass was developed. The procedure employes the finite element method and has two steps. In the first step the distribution of the initial stresses in the soil mass is calculated, with the assumption that these stresses will deform the soil and drive the failure once the soil has liquified. In the second step, these driving stresses are kept constant while the moduli and shear strengths are reduced to those corresponding to the state of liquefaction and the finite element method analysis is conducted again using the same mesh. The difference in deformations between these two steps represents approximately the permanent deformation of the liquefied deposit. This analytical method was used to simulate quite successfully the deformation patterns obtained in the shaking table tests, as well as the ground deformation trends in two liquefaction case histories. Encouraged by such relatively good capability of their method to predict deformations of liquefied soil mass, the authors used it to analyze several countermeasures for preventing large ground displacements. This comprehensive study is particularly valuable because, in addition to the shaking table testing, it also proposes a corresponding analytical procedure and discusses the applicability of such procedure to practical problems. In other words, the study clearly shows steps from model testing to the application of its results in engineering practice.

Sasaki, Tokida, Matsumoto and Saya in the paper "*Experimental Study on Lateral Flow of Ground due to Soil Liquefaction*" describe very interesting results of a series of large shaking table tests. The main objective of the investigation was to clarify the important factors governing the lateral flow and large ground displacements caused by liquefaction at flat or mildly sloped grounds. Eight different well instrumented models of liquefiable deposit were tested, seven in a 6m × 0.8m × 2m square box and one in a circular box 0.4m high with the diameter of 4m. All eight models were subjected to one-directional excitation. With respect to that, the circular model was tested to investigate the influence of the direction of excitation on the direction of lateral ground flow. To encompass the most common field situations, the models were build as the combinations of the following three layers of variable thickness: nonliquefiable bottom layer, a middle liquefiable layer and the top unsaturated layer. In different tests the slope, the extent and the average thickness of these layers were different. During and after the shaking the accelerations, pore pressures and displacements were measured within and at the surface of the soil deposit. The instrumentation was quite elaborate and densely spaced. Such good instrumentation and a relatively large number of well designed large scale tests yielded a number of important conclusions. Some of these conclusions are: (i) the ground surface displacements increase remarkably only after the excess pore water pressure exceeds about 80% of the initial effective vertical stress, i.e., before such large pore pressures develop the displacements are negligible, (ii) lateral deformations originally occur only in the liquefied layer, i.e., they do not occur in the unsaturated surface layer, which can, however, be displaced and deformed subsequently by floating and moving on the liquified layer in the direction of the slope, (iii) the magnitude of the ground surface displacement is predominantly affected by the thickness of the liquefiable deposit, the slope of the ground surface, and the duration of the excitation after almost complete liquefaction has taken place, while it is much less affected by the slope of the base of the liquefied deposit, and (iv) the lateral flow occurs almost exclusively in the direction of the ground surface slope regardless of the direction of ground shaking. The conclusions of this investigation can be used to critically examine some aspects of the liquefaction evaluation methods used currently in engineering practice. Particularly those methods which directly relate the ground surface accelerations to the rate of pore water pressure buildup, as well as those procedures which assume that lateral spreading occurs predominantly in the direction of shaking.

Soil-Structure Interaction

Kurosawa, Ryoichi, Izumi and Akino conducted two series of shaking table tests on small scale models. They examined the effect of the foundation embedment in a soft ground on the response of a small model of a reactor building and described the result in the paper titled "*Laboratory Tests on Embedded Reactor Building on Soft Ground*". First series of tests was conducted on the model of the embedded foundation without the structure, while the second series of tests was conducted on the model of the foundation and the reactor building. Three embedments were tested in each test series, full embedment, half embedment and the case with no embedment. To examine the vibration characteristics of the building model, the ground-foundation system and the ground-foundation-building system, a series of hammering test were carried out in addition to the shaking table tests. Also, two types of analytical simulation of the model tests were performed for comparison, a FEM analysis and an S-R (apparently swaying-rocking) foundation block analysis. To take into account scale effects, the soft ground in the shaking table testing was represented by a silicone rubber and the model of the structure was made of aluminum. The results of the investigation confirmed that, for the given test conditions, the embedding decreases the amplification of the motion of the ground-foundation system with respect to the input excitation of the shaking table, while it increases the radiation damping. In the case of the ground-foundation-building system it was confirmed that embedding again decreases the amplification of the motion of the structure, while the predominant frequency of the motion of the building increases. The comparison between the analytical and experimental results are discussed in terms of impedance functions, foundation input motions and structure response.

Hibino, Moriyama, Izumi and Kiya in their paper "*Laboratory Tests on Embedded Reactor Building on Hard Ground*" describe the results of a shaking table study very similar to the study described above using practically identical approach and geometry of the models. However, to simulate a hard ground a hard silicone rubber was used to represent the surrounding soil, while a soft silicone rubber was used as embedment material to fill the foundation excavation. As indicated by the authors, some of the test results are quite complex and could not be straightforwardly explained. However, the results confirmed that embedment increases predominant frequency of the soil-structure system and radiation damping.

CENTRIFUGE TESTS

K. Suzuki, Babasaki and Y. Suzuki describe in the paper "*Liquefaction Test by a Laminar Box in a Centrifuge*" how the liquefaction at level ground can be successfully simulated in a centrifuge. To allow development of shear strains in saturated sand corresponding to the strains generated during the vertical propagation of seismic shear waves, they constructed a laminar box. The authors accounted for the scaling effects by using glycerin solution instead of water. During centrifuge test the shaking accelerations and pore pressures were measured at several important points within the saturated sandy deposit. The results show a good agreement with the corresponding observations made during and after full liquefaction in the field. Such experiment, which belongs to a class of centrifuge tests in which stacked rings are used to allow simulation of 1-D shear behavior, is not conceptually new. Similar experiments were conducted earlier by several research teams, as indicated by the authors. The results of these previous studies generally agree with the acceleration and pore pressure response results described in the paper. The design of the new laminar box, which is described in detail, is apparently successful and such developments and improvements in the field of centrifuge testing should be encouraged. This is particularly important for further investigations of the liquefaction phenomena which, although extensively studied for the last 20 years, are still not entirely explained.

Lenke, Pak and Ko demonstrated in their paper "*Centrifugal Modeling of a Pile under Vertical Random Excitation*" that a centrifuge is capable of modelling theoretical results of a single pile response subjected to a random vertical vibration. The experimental data were compared with a corresponding theoretical analysis of the vertical compliance of a pile. The experimental and analytical results are found to be in a good agreement. Consequently, the authors suggested that the testing technique used here for a single pile may be improved and applied to more practical foundation problems like, for example, vibration of a pile group. In that sense, this work apparently represents a preliminary study for more complex future dynamic soil-structure investigations. To minimize the reflection of waves from the centrifuge box boundaries a layer of a sealing material called Duxseal was used.

LARGE SCALE FIELD TESTS

Watabe and his co-workers (14 authors) in the paper "*Large Scale Field Tests on Quaternary Sand and Gravel Deposits for Seismic Siting Technology*" describe an extremely interesting and valuable investigation of the cyclic response of two in-situ circular columns of gravelly soil of a large size of 10 m in diameter and 5 and 9 m height, respectively. The circular field columns were separated from the surrounding soil by trenches filled with a suitable relatively frictionless material. The columns were vertically loaded by concrete blocks to generate effective stresses corresponding to the stresses usually applied by a nuclear reactor building. The investigation was conducted to evaluate the suitability of gravelly and similar quaternary deposits for the sites of nuclear power plants. On the top of the concrete blocks were mounted exciters for the generation of small strain high frequency torsional cyclic loads. In addition to that, the block sitting on the 9 m deep column was connected to a big concrete reaction block with two jacks, which were used for subsequent application of larger strain low frequency cyclic torsional loads. Apart from these two circular columns, on the same site a large concrete square block was placed directly on the ground surface. This block was also connected to the same reaction block with two jacks for the application of one-directional larger amplitude cyclic loading, and on its top four exciters were mounted for independent dynamic excitation in two perpendicular directions. As an integral part of this comprehensive field model testing project, the classification tests, standard field tests, static laboratory tests and cyclic laboratory tests were performed as well. It should be noted that the laboratory static and cyclic properties of the gravel were accurately determined on intact specimens obtained by the in-situ freezing technique. The results of the field model tests showed that the site investigated, and hence the similar quaternary sites, are suitable for the construction of nuclear power plants. From the point of view of the machine foundation design, geotechnical earthquake engineering and the cyclic behavior of saturated gravelly materials, the results obtained are extremely interesting and important. It may be concluded that the field columns were constructed and tested so well that they resembled rather closely solid cylinder specimens torsionally sheared in a triaxial cell. The cyclic behavior of field columns was indeed very similar to that typically obtained in a torsional solid cylinder triaxial test, especially if the comparison is made using the, so called, strain approach, i.e., by relating the level of cyclic shear strains to the settlement (densification) and residual pore water pressure buildup. For example, no pore water pressure developed and no settlement was reported below the threshold shear strain, which is for clean sands and gravels typically $\gamma_t \approx 10^{-4}$. On the other hand, when the cyclic shear strain of approximately 10^{-3}, which is larger than γ_t, was applied, a noticeable settlement was recorded. Also, the authors concluded that the residual pore pressures must have developed, although they were not directly recorded since, as they were being generated, they simultaneously dissipated due to a slow cyclic loading and large permeability of gravel. The behavior of the in-situ columns under different levels of cyclic shear strains was also in a perfect agreement with the shear modulus reduction and damping curves obtained in the laboratory on the gravel specimens. It would be extremely interesting to know how the same field columns would behave under larger cyclic shear strains, when larger pore pressures and settlements should develop.

Fujimori, Tsunoda, Izumi and Akino presented in their paper "*Large-Scale Model Forced - Vibration Test Comparison of Test Results on Hard and Soft Ground*" another very interesting large-scale field model test. They performed vibration tests on two identical reinforced concrete models of a reactor building structure having the base of 8 × 8 m and the height of 10 m. In one test the structure was placed on the surface of a soft stratified soil deposit approximately 8 m thick which is underlain by a stiffer deposit, while in the other test the structure was built on the surface of a uniform hard deposit. The structure was not embedded. However, in both cases the soil-structure interface was at the bottom of an open excavation 5 m below the original ground surface. The vibration was applied in the sinusoidal mode in one horizontal direction via an exciter placed on the top of the model structure, or an exciter placed lower at the top of its foundation block. The response of the whole system to forced vibrations at predetermined frequencies was recorded in terms of displacements at different points of interest, accelerations of the structure and surrounding ground and contact pressures at the soil-structure interface. In addition to the field tests, a finite element method (FEM) was employed to examine whether the field responses can be reproduced analytically. Based on the results of the field tests, the corresponding FEM analysis and their comparison, the following main conclusions were derived by the authors for the given test conditions: the radiation damping on the soft ground was in general greater than that measured on the hard ground, the response of the surrounding ground was rather complex (most probably due to the fact that the soil-structure interface was below the ground surface at the bottom of excavation) and the response of the whole soil-structure system can be rather well described by the FEM analysis used.

PILE LOADING TESTS

Lateral Loading

Golait in his paper "*An Approach to Characterize Cyclic Deflection of Piles in Calcareous Soil Media under Offshore Wave Loading Condi-*

tions" presents a small-scale laboratory pile model tests in artificially prepared calcareous sand. Piles were made of stainless steel pipe 25.4 mm in diameter with various length to diameter ratios between 10 and 50. The surface of the piles was roughened to simulate the prototype offshore piles. A simple mechanical system was used to apply different modes of cyclic lateral and static loads at the top of the pile which was installed in a masonry tank. The interpretation of the test data is based on the concept of a cyclic deflection resistance parameter. The approach is innovative and convenient because it characterizes the pile deflection in a normalized form and can be therefore easily employed for the real size piles. It should be noted that the number of loading cycles applied in the tests is relatively small. In the real ocean environment, an offshore platform may be subjected to much larger number of waves. During a North Sea storm, for example, besides a larger number of waves, the amplitude of the waves increases to a maximum and then gradually decreases. It would be interesting to see whether or how the author's model or relationships can be modified to simulate the permanent lateral deflections of the piles during such storms.

Hakulinen in "*Measured Full-Scale Dynamic Lateral Pile Responses in Clay and in Sand*" summarizes results from full-scale pile experiments conducted on four single piles and a pile group. Two types of piles were used, reinforced concrete piles and steel piles filled with concrete. The models were excited by random and sinusoidal loads applied via a hydraulic loading system. From the response the natural frequencies, natural modes and the stiffness and damping of the pile-soil systems were calculated. These results were then compared to the corresponding values obtained by two analytical methods currently used in practice. The analytical results were derived based on soil properties determined directly in-situ or in the laboratory. The study shows that experimentally obtained stiffness agreed very well with the analytical values, while the analytically obtained values of damping overestimated the experimental results. Dynamic soil-pile interaction, especially during lateral loading of a pile group, is one of the more complex soil-structure interaction problems engineers face today. The author stressed that there are quite a few theocratical solutions in the pile dynamics, while in contrast with that there have been relatively few dynamic loading tests published to date. It is hoped that the author will publish the complete results from his experiments. Such data can enhance the state of knowledge on the subject.

Axial Loading

Janes, Bermingham and Horvath in the paper "*An Innovative Dynamic Test Method for Piles*" suggested a new method for conventional testing of the ultimate capacity of a pile. The system described involves using solid propellant fuels to accelerate a reaction mass mounted on top of the installed pile within a specially constructed pressure chamber. The fuel within the chamber is burned in a controlled manner thereby forcing the reaction mass upwards. As a reaction to that the pile is being pushed downwards. The event last approximately 0.1 seconds which produces vibrations of a frequency of approximately 10 Hz. This frequency is well below a typical natural frequency of most soil-pile systems, and the influence of stress waves is therefore insignificant. Thus, the device is applying to the pile something similar to a temporary push. Consequently, such method might be an alternative to the static load test which is time consuming and usually more expensive, or to the dynamic pile driving test which produces high impact forces. With respect to the rate of loading, the test proposed, which is called the Statnamic test, seems to be somewhere between the static and pile driving test. The effect of the rate of loading with respect to the type of soil is discussed. The authors show excellent correlation between the static and Statnamic load-displacement behavior in elastic range. The correlation holds very well up to the loads equivalent to two times working load, which is the proof load for most foundations.

Laboratory Shear Rod

Amar, Lepert, Levacher and Boisard in their paper "*Shaft Resistance During Driving in Clay from Laboratory Tests*" describe a new design and results of a test, called also shear rod test. In such test a solid rod is driven into or is built in the soil specimen in the laboratory and is tested under the conditions similar to the field pile loading conditions. The test was performed on samples of normally consolidated kaolinit clay. The analysis of the stress waves propagating in the rod during driving provided a good estimation of interaction forces, rod velocities and its displacements in the sample. Relationships were established between the interaction force, the energy dissipated in the soil, the velocity and the displacement of the rod, and the confining pressure of the sample. Observations and relationships were in turn used to identify the physical phenomena occurring at the soil/pile interface during the driving and to establish a law governing this interaction. The results presented should therefore be of interest to researchers developing new constitutive models for soil/pile interaction.

TESTS WITH EXPLOSIVES

Phillips and Luke describe in their paper "*Tunnel Damage Resulting from Seismic Loading*" a unique field experiment aimed at evaluation of the seismic response of a proposed underground high-level nuclear waste depository. The authors discussed that despite the fact that the damage to underground openings from ground shaking is less severe than that sustained by surface structures, and that major damage usually involves movement along faults that intersect the opening, it is still very important to asses possible seismic damages for important underground structures. Because there is rarely a ground motion measurement located at the point of damage, correlations of ground motion to observed tunnel damage have largely been based on the estimates of ground motion rather than observations and measurements. In an effort to provide a data set that includes both measured ground motions and documented tunnel response, an experiment was designed and conducted 0.5 km from a recent underground nuclear explosion which producedshaking equivalent to a Richter local magnitude of 5.0. Although the motions and damages resulting from earthquakes are expected to be larger than from nuclear explosions, and therefore more significant in design, the experiment is useful because it is difficult to collect underground data from earthquakes. In contrast, underground nuclear experiments are usually conducted on a regular basis and present an opportunity to obtain similar useful data. Experiment was conducted in a pre-existing tunnel along a 12 m section. It consisted of acceleration measurements, permanent displacement measurements, tunnel convergence measurements, borehole observations, still photography, and high-speed photography. The experiment produced a set of data consistent with case histories in the literature. The applicability of the data to predict seismically induced damages of the proposed waste depository is described. It should be noted that some acceleration values measured during the experiment were extremely high (up to 27 g), compared to the level of ground shaking usually measured during strong earthquakes.

LARGE SCALE AND OTHER SPECIAL LABORATORY TESTS

Large Scale Triaxial Test

Siddigi and Fragaszy in the paper "*Cyclic Strength Evaluation of Rochfill Dams*" suggested a method how to use a standard size triaxial specimen of 2.8 inches in diameter to characterize the behavior of gravels containing certain fraction of large particles (cables and large gravel particles) that would require testing of the large size 12.0 inches diameter specimens. The diameter of soil specimen is controlled by the maximum grain size, and the testing of such large specimens is expensive and the equipment is not commonly available. Given a typical minimum ratio of specimen diameter to maximum grain size of six, for the conventional triaxial specimen diameter of 2.8 inches all particles larger than approximately 1/2 inch are then "oversize" and must be removed before testing. To overcome the problem of "oversize" particles several procedures have been used in practice with limited success. The authors discussed that, depending upon the quantity of oversize grains present in the prototype material, these oversize particles may exist either in a "floating" or "non-floating" state. In the "floating" state the oversize particles are not in contact with each other and are "floating" in a matrix of smaller grains. In the "non-floating" state there is a continuous grain-to-grain contact between oversize particles, and the matrix soil merely fills the voids created by the structure of these oversize grains. Based on that the authors concluded that for the gravels in "floating" state, the test results obtained for the soil matrix alone (with no oversize grains) will predict the cyclic behavior of the prototype material regardless of the percent of oversize particles, as long as the tests are performed at the same relative density (not the same absolute density) as that of the prototype material. To test their hypotheses the authors conducted a cyclic triaxial testing program on two types of gravelly soils. Both, large size 12.0 in diameter specimens of original total material and the standard size 2.8 diameter specimens prepared only from the matrix material without oversize grains were tested, and the results were compared. For each triaxial test, the number of cycles required to cause a residual pore pressure of 100% (initial liquefaction) was determined, as well as the number of cycles required to cause 2.5%, 5%, 10% and 20% double amplitude axial strain. The test results confirmed the validity of the authors' hypothesis. They concluded that the cyclic strength behavior of gravelly soils containing particles too large to be incorporated in a standard size triaxial specimen may be modeled by scalping the oversize particles and testing the remaining matrix material, provided the oversize particles are "floating" in the soil matrix.

Shear Wave Velocity Measurements

Yan and Byrne describe in their paper "*Stress State and Stress Ratio Effects in Downhole and Crosshole Shear Wave Velocity Tests on Sands*" how the effects of the in-situ stress state and stress ratio on the value of the maximum shear modulus in sands can be evaluated in laboratory by downhole and crosshole seismic testing technique using piezoceramic bender elements. In other words, in-situ K_0 conditions were recreated in a laboratory model specimen and shear waves simulating the waves in crosshole and downhole seismic field testing were propagated through the specimen. As pointed out by the authors, such investigation is important because studies of soil stress state and stress ratio effects on the shear modulus, G_{max}, performed in the laboratory using the resonant column device, or recently using the true triaxial device (where a cylindrical or cubical soil sample is subjected to shear wave measurements under a stress controlled boundary conditions) usually do not reflect true in-situ K_0 conditions. In the field, seismic tests are normally performed under the "zero lateral strain" K_0 condition. The in-situ stress distribution was simulated in the laboratory along the height of the specimen by, so called, hydraulic gradient similitude (HGS) procedure. The procedure involves the application of high body forces to the soil by means of downward seepage applied under a controlled hydraulic gradient. This technique is similar to the centrifuge technique in increasing the soil stresses in the model. The specimen of sand was apparently prepared in a rectangular container with dimensions 460 × 200 × 420 mm. For downhole tests, an array of bender elements rigidly mounted on small bearing plates was connected to a rod installed in the sand simulating the downhole condition. The top bender element was installed near the sand surface with its tip down, and used as a shear wave source during the tests. For crosshole tests, two elements were assembled at the same elevation in the sand, but on different rods installed at a certain horizontal distance. These two elements were aligned vertically to prevent blockage of water flow, thus they generated and received an SH wave within the horizontal plane, which is similar to the in-situ crosshole test. The main conclusion of the study is that the shear wave velocity is more directly related to the individual stress components in the wave propagation and particle motion directions, i.e., the individual stress method suggested for the determination of the G_{max} modulus should be used rather than the method which relates G_{max} to some average stress. Such conclusion is in agreement with some previous studies. This interesting investigation shows how a relatively new concept of the utilization of bender elements to propagate and record waves in a soil specimen can be successfully applied in a more complex laboratory model testing.

Special Specimen Preparation

Yan and Williams show in their paper "*Deformation of Reconstituted Clay under Cyclic Loading*" how reconstituted soft clay triaxial specimens can be prepared by means of a vacuum preloading. The specimens were subsequently tested under static and cyclic loading in undrained conditions and the results were analyzed. Initially, a clay slurry with a moisture content of about 71% was prepared. The slurry was poured into a 1000 mm by 500 mm container, over which a rubber membrane was placed. The membrane was then sealed air-tight and a pump connected to the container through a pipe to remove the air and excess water from the slurry. To accelerate drainage, a geotextile layer was placed adjacent to the inner wall of the membrane. A vacuum pressure was maintained at the membrane to preload the sample. Specimens 50 mm in a diameter and 120 mm high, cut from the reconstituted clay block were used for both the static and the cyclic triaxial compression testing. In general,the specimens were normally consolidated and in no case the specimen was more than lightly over-consolidated. With respect to the results of cyclic tests and their comparison to the static tests conducted under the same initial stress conditions, the authors concluded that the relationship between the residual pore pressure, normalized to the mean initial effective consolidation stress, and cumulative axial strain is unique for a given consolidation stress ratio. Also, they found that the effective strength parameters for reconstituted clay, determined following cyclic loading, are identical to those determined in static triaxial tests. The preparation of laboratory clay by vacuum is not a new technique, and the test results presented further verify its usefulness. The conclusions about the applicability of the effective stress concept for the cyclic characterization of normally consolidated clay are also in agreement with several previous similar studies. It should be noted, however, that cyclic studies on overconsolidated clays show that the effective stress principles cannot be applied in the same manner to the overconsolidated clays.

POINTS TO CONSIDER

In soil dynamics and geotechnical earthquake engineering there has always been a concern that the commonly used engineering methods for the evaluation of the seismic stability of soil-structure systems might be inadequate, especially for critical structures such as the nuclear power plants, nuclear waste disposal and offshore platforms. There has been an awareness that many phenomena are so complex that they cannot be modelled accurately enough with available dynamic analyses coupled with standard dynamic soil testing on small specimens. During the period from the late sixties very great advances have been made on the analytical front, fueled by the prolific development of the Finite Element Method and the phenomenal growth of the computers. On the other hand, due to the painstaking and time consuming processes associated with experimental research, the progress made with laboratory testing, as well as field testing of soils, while significant, has been much slower. Such situation created a need for elaborate model testing which can be used to simulate directly more complex soil dynamics problems. The results of model testing can then be (1) used to clarify mechanisms of failures and deformation for complex conditions, (2) to verify the accuracy and applicability of analytical and empirical engineering methods, or (3) to develop new methods or improve the existing ones. With exception of just a few papers, the investigations described in this session are all aimed at one or more of these three specific goals.

Having so many different types of tests described in this session with each test being quite sophisticated and unique, many points for discussion can be put forward. Below are just a few which seem to be of interest:

- In the case of small-scale model testing more attention should be payed to the effects of scaling. This is not important only for the centrifuge models but also for the small-scale models tested on the shaking table and other similar small-scale models. More comprehensive discussions on this aspects of model testing are necessary to clarify their limitations and evaluate their usefulness in practice.

- In the models built in a box the effect of boundaries which reflect waves may pose a serious problem. A careful evaluation of the degree to which such effects may influence the outcome of the test is desirable and should be an integral part of any investigation.

- Although not many centrifuge tests, shaking table tests or large-scale field tests have been conducted and published to date, as compared to other geotechnical cyclic laboratory tests or field tests, a careful comparison between similar tests and synthesis of their results may yield very useful conclusions and point in the direction where further improvements are needed.

- Several papers describe truly impressive large-scale model field tests. The cyclic shear strains applied in these tests however, were rather small, i.e., these tests were nondestructive. Given the strains generated by earthquakes which maybe considerably larger, the question arises whether such tests can be conducted with larger strains, and also, what would be the consequences for testing facilities and what would be the cost relative to the small strain tests.

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