CENTRIFUGE RESEARCH OF LIQUEFACTION PHENOMENA

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SUMMARY

This paper describes research currently ongoing to investigate many aspects of earthquake engineering related to the prediction, and further understanding of liquefaction and liquefaction related effects. This research incorporates physical centrifuge modeling utilizing state-of-the-art equipment including earthquake actuators, containers, and data recording instrumentation. Research concerning one particular instrument, the in-flight cone penetrometer, will be discussed in detail in this paper with results. Other ongoing research will also be briefly discussed. The bulk of this research is being conducted at the centrifuge research center of the Waterways Experiment Station, and the rest at the centrifuge center at Rensselaer Polytechnic Institute.

INTRODUCTION

In spite of major advances over the last 25 years, serious gaps in our knowledge base still exist. Especially in the areas of earthquake hazard predictions, site characterization for seismically sensitive parameters, constitutive behavior and material properties of rock, soils, and composite (reinforced) materials under seismic loads, and the stress and deformation responses of sites and facilities to seismic loading. Economical remediation and defensive design techniques are needed in addition to careful calibration of fast advancing numerical methods to actual field performance. In order to address these issues, there is a need for a consistent research program, which will produce design tools, and criteria that incorporate innovative measures for increasing the seismic safety of engineered facilities. This paper presents research currently being conducted to reduce damage from a potentially devastating earthquake by advancing state-of-the-art knowledge of earthquake hazard assessment, seismic design, and remediation of infrastructure, and by developing technical capabilities to improve response to earthquake-induced life-threatening emergencies. This research, as being conducted by the Waterways Experiment Station (WES), consists of numerous thrusts, one of which will be discussed, in this paper. This thrust consists of improved procedures for predicting liquefaction related effects based on cone penetration data. Other areas of research not directly addressed in this paper include implementation of equipment for evaluating liquefaction effects, behavior of liquefying soils, and failure mechanisms and damage assessment. All of the fore-mentioned research is being performed through physical centrifuge modeling, most at the U.S. Army centrifuge research center located at WES, and some at the centrifuge research center located at Rensselaer Polytechnic Institute.

Physical modeling of field problems generally involves the construction and experimentation with scale models of a prototype or field structure. The response of the model to a physical perturbation such as cyclic loading, or earthquake motions can be measured and interpreted in terms of the field problem under consideration. Realistic model behavior data can provide valuable information for designers about failure mechanisms and long term performance. In many engineering fields, particularly geotechnical engineering, gravitational effects dominate

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performance. Where the behavior of a material is stress dependent, such as with the engineering properties of soil, then simple scaling of a field problem and experimental investigations on the laboratory floor will give erroneous results. Modeling in the laboratory at 1/50 scale for instance, the effective confining stresses in the soil would be 50 times less than those same stresses in the field. The use of a centrifuge however, overcomes this modeling error by increasing the weight of each particle in the model by an equivalent number of gravities. Generally the linear scale of the model and the number of gravities are chosen to be identical. Therefore, a 1/50-scale model of a 20 m high earth slope would be 400 mm high. Under a steady acceleration of 50 gravities (approximately 500 m/s^2), the model would have identical self-weight stresses at equivalent points in the model and in the prototype. Each soil element in the centrifuge model is subject to the same stress path as its equivalent element in the full-scale prototype. The centrifuge can recreate a wide range of field phenomena and environments under laboratory conditions, generating realistic data to verify and validate computer simulations and engineering analyses.

LIQUEFACTION PREDICTION WITH CPT

Most of the liquefaction type failures observed in the field have occurred at sites, which were not instrumented. The corresponding lack of quantitative observations has slowed down the development of reliable analysis techniques to evaluate the characteristics and consequences of soil liquefaction. The advent of the geotechnical centrifuge physical modeling methodology has helped in this respect, by offering the ability to create fairly realistic full-scale stress states with uniform and measurable soil as well as foundation properties. The centrifuge has been used to study the mechanisms involved in liquefaction, and to validate numerical codes, both for free field and soil-structure interaction conditions.

Design methods for shallow and deep foundations have been proposed on the basis of cone resistance. A number of laboratory studies have been conducted with the cone penetrometer in calibration chambers. In these tests either a cone of reduced size was tested in order to minimize the boundary effects or a full size cone was tested to represent field conditions at the appropriate overburden pressure level. In either case, it is necessary first to develop scaling relations for extrapolating the model test results to the full-scale cone. Secondly, it would be necessary to account for the effects of the self-weight body force gradient present in field applications, which could not be simulated in the calibration chambers. To ensure that the gravity stress gradient present in field applications is properly represented in laboratory testing, a centrifuge can be employed. If the soil models are carefully prepared so that the properties are controlled and known, then models of the cone penetrometer tested in the increased gravity environment should produce penetration resistance profiles that can be related to fundamental soil properties.

A number of studies have been performed in Europe and the United States attempting to model the CPT and similar static penetrometers in the centrifuge. While both clay and sands have been investigated, experiments on sand models will be discussed in this paper. Several investigators have reported results of centrifuge modeling of the CPT [Corte et al., 1991; Renzi et al., 1994]. In these studies several important aspects of CPT centrifuge modeling were clarified and the reader is referred to those publications. Basic scaling laws indicate that a miniature cone of diameter d_c used in a centrifuge test at a centrifugal acceleration of n gravities, models a prototype penetrometer (d_{cp}) in the field (that is at 1 g) of diameter, $d_{cp} = nd_c$. The conclusion is that as long as the nd_c value equals the field penetrometer diameter of 36 mm, then the two results are comparable. This paper will present current findings of research conducted with a miniature cone penetrometer suitable for in-flight centrifuge testing on soils placed at various states of stress. These findings are combined with results from centrifuge testing on liquefaction to develop relationships for determining liquefaction related effects such as thickness of the liquefied layer and amount of lateral spread.

Modeling of earthquake events using a centrifuge has been established as a powerful technique over the past decade, especially in the area of liquefaction. With the advent of new actuators to simulate earthquakes and new containers aimed to mimic the dynamic stiffness of the soil being modeled, [Van Laak et al., 1994; Madabhushi et al., 1998] the potential of centrifuge testing has steadily grown. Centrifuge work on liquefaction, lateral spreading, and their effects on shallow and deep foundations as well as buried facilities and port structures has continued in the U.S. and Japan [Taboada and Dobry, 1998; Fujiwara et al., 1998]. This paper presents results from centrifuge research on liquefaction effects for a 10 and 6 m thick deposits of clean sand shaken with two different peak accelerations.

Centrifuge results reported in this paper are from in-flight CPT and liquefaction effects on several relative density, saturated Nevada sand models [Sharp et al., 1998]. The sand was placed dry using the sand raining technique. From the CPT testing, unique plots of tip resistance versus vertical effective stress for each relative density model were determined. From these data, it is possible to determine a unique value that describes each

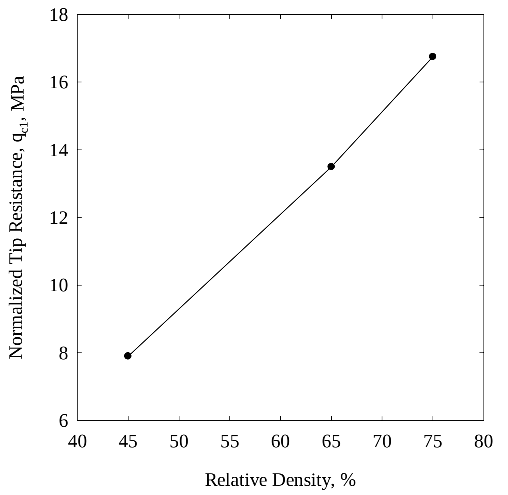

Figure 1: Corrected tip resistance versus relative density for Nevada sand

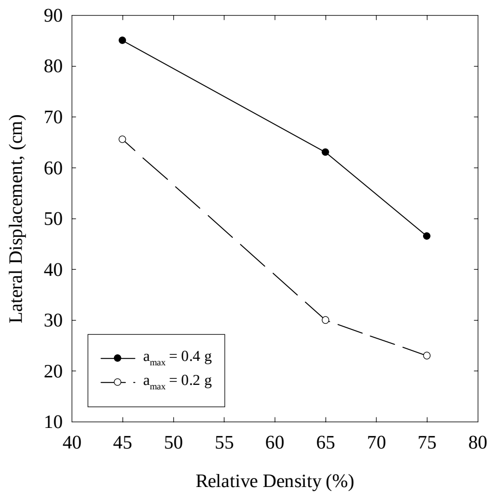

Figure 2: Lateral displacement versus relative density for Nevada sand

relative density model as reported by [Olsen, 1994]. This value is the corrected tip resistance q_{c1} and is shown in Figure 1, versus relative density. For the same relative densities of the CPT tests, models were constructed and tested on the centrifuge for liquefaction effects utilizing a laminar box and earthquake actuator [Sharp, 1999]. These models give results for thickness of liquefied layer, amount of lateral displacement, and amount of settlement for a given soil deposit. These results lead to plots such as shown in Figure 2, for lateral displacement versus relative density. Combining the CPT results of Figure 1 with the liquefaction results of Figure 2 allows the elimination of relative density and a plot as shown in Figure 3 where lateral displacement is now shown versus corrected tip resistance. This plot represents the development of a prediction chart allowing a direct correlation between a field measurable parameter, q_{c1}, and resulting earthquake damage, lateral spread.

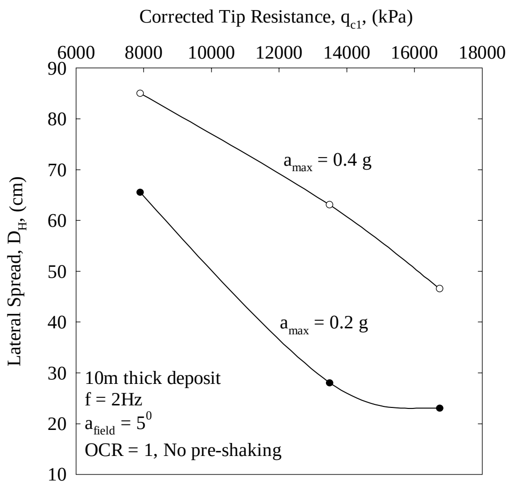

Figure 3: Lateral spread versus corrected tip resistance for Nevada sand

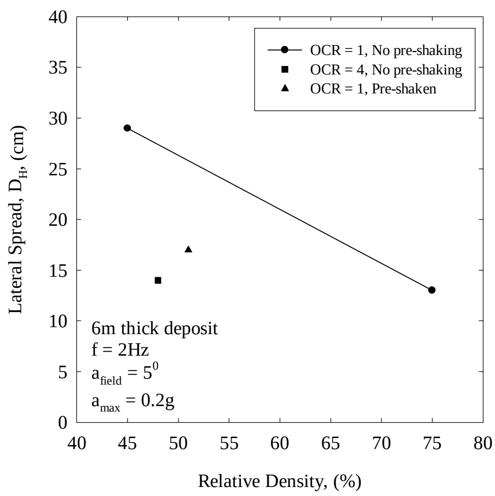

Figure 4: Lateral spread versus relative density for Nevada sand

In order to enhance the usefulness of these charts, tests were conducted to investigate the naturally occurring stress states of overconsolidation and past loading histories. These tests include both centrifuge CPT and liquefaction testing on models that were overconsolidated or pre-shaken. The reader is referred to [Sharp, 1999] for details concerning this testing and results. It was discovered that the cone penetrometer is sensitive to both overconsolidation and pre-shaking as the tip resistance increases dramatically in such models as compared to those with no overconsolidation or pre-shaking. Conversely, the liquefaction effects (thickness of liquefied layer, amount of lateral spread, and settlement) are seen to decrease with overconsolidation and pre-shaking as compared to those with no overconsolidation or pre-shaking. These results are shown in Figures 4 and 5. In

Figure 4, lateral spread is plotted versus relative density without the incorporation of the CPT results. In Figure 5, lateral spread is plotted versus corrected tip resistance and it is clear that the 45% relative density models that were overconsolidated and pre-shaken are not behaving as the 45% relative density model with no overconsolidation or pre-shaking. The implication of these results being that the cone penetrometer will correctly incorporate the stress states of the soil and those effects can be incorporated into prediction charts of liquefaction effects versus corrected tip resistance.

There are a number of factors that have been shown to influence the effects that occur at a site as a consequence of liquefaction. They include but are not limited to input peak acceleration, permeability, deposit thickness, site topography, and earthquake parameters (frequency, duration, and magnitude). Not all of these parameters have been addressed in the results presented in this paper. More information about these factors and related research can be found in [Taboada and Dobry, 1998; Sharp, 1999]. Within the limits of the research, the final predictive chart for lateral spread versus corrected tip resistance is shown in Figure 6. In the work of [Sharp, 1999] can also be found similar results for thickness of liquefied layer versus corrected tip resistance and settlement versus corrected tip resistance.

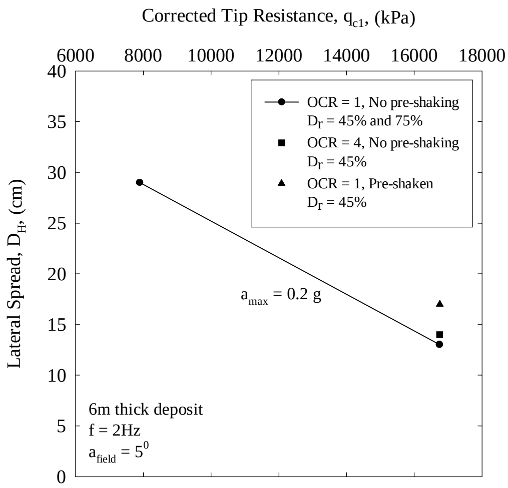

Figure 5: Lateral spread versus corrected tip resistance for Nevada sand

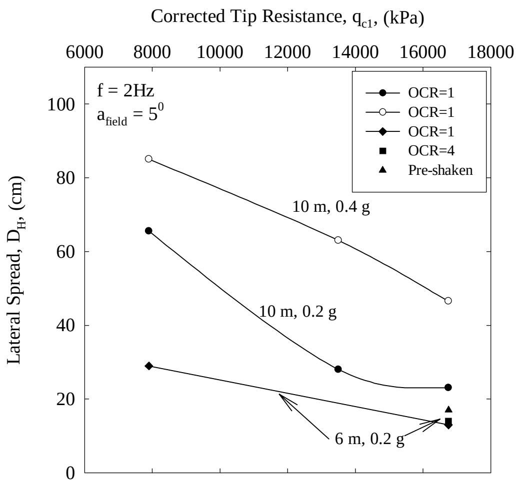

Figure 6: Lateral spread versus corrected tip resistance for Nevada sand, 10 and 6 m thick deposits

BEHAVIOR OF SOILS

The present state-of-practice for determining the performance of soils that undergo earthquake-induced shear-strain and consequently pore water pressure buildup in saturated soils is to determine if a soil will or will not liquefy. The performance and safety of structures are based on rigid sliding-block/slices limit-equilibrium methods to determine slip-plane stability and deformation using residual strengths in the case of liquefaction.

In-situ methods such as Standard Penetration Test (SPT), Cone Penetration Test and shear wave velocity measurements are used to define the triggering of liquefaction. The potential for liquefaction relies on empirical correlation between the penetration resistance and the performance of soil deposits in past earthquakes [Seed, 1979]. The database on triggering liquefaction is based on data from level ground where surface evidence occurred. Soil conditions were shallow at overburden pressures less than about 95.8 kPa (about 4.6m of depth). The database is normalized to an earthquake of magnitude 7.5. Corrections for other earthquake magnitudes have to be made [Seed & Harder, 1990, NCEER, 1996].

To extend the database to depths representative of foundation soils under dams requires the use of correction factors [Seed & Harder, 1990] for the effects of overburden pressure and initial static shear stress. Correction for high overburden, $K\sigma$, is based on laboratory test results of the ratio of cyclic-shear-stress, CSS, to cause liquefaction at an overburden effective-stress state, σ'_o, to that at a σ'_o = 95.8 kPa. Correction for initial static shear stress, $K\alpha$, is based on the ratio of CSS to cause liquefaction with initial static shear stress applied to that at no initial static shear stress.

The correction factor $K\sigma$ has a large influence for dam foundations. It can reduce the CSS to cause liquefaction to about 45 percent of its in-situ value at pressures about 670 kPa that would exist beneath an embankment dam about 30.5m high. Alternatively, if we were deriving SPT criteria for remedial treatment of this dam to limit the potential level of earthquake generated pore water pressures, the $K\sigma$ factor would cause an increase of more than double in the required penetration values to be measured in the field. Clearly, the correction factor can have a major impact on the potential for triggering liquefaction or the excess residual pore water pressures and on the cost of remediation. The correction factor $K\alpha$ can also contribute significantly to the reduction of the in-situ strength. However, for relative densities above 45-50 percent, $K\alpha$ can have a positive effect on the in-situ strength.

In application of the state-of-practice, we inherently make the following assumptions: (1) the soil is always undrained, (2) liquefaction occurs instantaneously and the soil shear strength jumps to residual state, (3) residual strength is constant with monotonic loading, (4) liquefaction is independent of soil zone thickness, permeability, or boundary conditions, (5) liquefaction is independent of when the earthquake peak energy arrives, (6) behavior of the liquefied soil and its resultant effects on a dam are independent of the soil zone thickness, permeability, and boundary conditions, (7) dam stability and deformation are controlled by slip-planes independent of the liquefied soil zone thickness and behavior, and (8) non-liquefied soil at a site is unaffected by the earthquake. Field behavior, numerical analyses, and physical model tests show that these assumptions are invalid.

Significant progress is being made in the development of numerical methods for analysis of liquefaction and the consequences. However, the engineering profession will most likely always use empirical correlation (Seed's or others) of in-situ measurements versus potential liquefaction, pore water pressure generation and earthquake response. Every time a site is evaluated for a seismic design or potentially liquefiable soil is improved and a dam remediated, in-situ measurements will be made. A value/range of in-situ measurement to achieve will be specified for a construction/remediation contractor. Some in-situ measure will be used to judge soil conditions/improvement and seismic safety of a dam or site. Therefore, improvement in our current state-of-practice and the empirical correlations between in-situ measures and performance of soil deposits has to be made. Current studies of the seismically-induced deformation behavior of dams indicate that as soils are progressing toward liquefaction (pore water pressure is increasing and shear strain is occurring) significant deformations of the structure can occur. Failure (damaging levels of deformation) can develop significantly before the complete initial liquefaction stage (100 percent pore water pressure ratio) is reached. Depending on specific conditions involving the location, depth and extent of liquefying soil and the driving forces, a structure may fail at only 50 percent strength reduction. In this case, remediation to assure safe performance is required to prevent serious damage significantly before an initial liquefaction condition and a residual strength stage are arrived at in the soil.

The problems in the current state-of-practice stem mainly from the fact that we do not know for the sites that have liquefied and constitute the empirical basis for analysis: (1) the exact and complete soil conditions and profiles, (2) the real behavior that occurred in the soils during and after the earthquakes or the various influences on the behavior, (3) that the assumed non-liquefied soils (used in comparison to liquefied soils) did not develop pore pressures or strains and change state during the earthquakes, and (4) whether artificial and possibly incorrect conditions in laboratory testing may have led to conclusions not totally applicable to the field behavior. Improved definition and physical evidence is needed of the processes and mechanisms involved as a soil progresses to liquefaction and residual strength. This is needed to allow refined analyses for dam safety and more cost-effective and safe remediation design and analysis. Because we can make various assumptions coupled with methodologies and numerical analyses that can give solutions or answers to most anything, the reality-check of solutions must come from field or equivalent-field data of behavior under well known and defined conditions. The earthquake response database needs to be expanded with more complete data to provide: (1) the necessary advance in the state-of-practice, (2) a basis for modification and improvement of current methodology and assumptions, and (3) definition of the physical processes and mechanisms involved in the liquefaction process and resultant effects on dam behavior. This would also provide the fundamentals and basis for development of new methodology and analyses. New methodologies have to be based on correct mechanisms and processes.

Centrifuge testing is being used to produce prototype response under laboratory conditions and with measured base shaking input motions and propagation. The experiments are to: (1) obtain high-quality detail and data for earthquake behavior case histories, (2) investigate the $K\sigma$ and $K\alpha$ correction factors under dynamic loading by shaking of the continuum rather than by laboratory element tests, (3) measure and investigate pore pressure behavior and response under various conditions during and after earthquakes, (4) measure and investigate strain, deformation, and softening behavior during and after earthquakes, (5) measure and investigate the controlling effects of permeability on pore pressure behavior during and after earthquakes, and (6) measure and investigate the effects of boundary conditions on the behavior of liquefying soil. Each centrifuge test will yield results relevant to several of the objectives in defining the behavior of liquefying soils and effects on dam response. Laboratory testing will be used to: (1) develop and define the complete shear stress-strain curve for earthquake-induced liquefying soil behavior including the residual portion and the development of simplified methods for obtaining the curve, (2) determine the properties of soils used in the centrifuge dynamic tests for both pre and post test conditions, (3) determine the complete shear stress-strain curve for the soils used in the centrifuge dynamic tests and (4) conduct cyclic tests for the laboratory-based determination of $K\sigma$ and $K\alpha$ for comparison to the centrifuge dynamic test results.

Analytical procedures employing both numerical dynamic-analysis and conventional static-analysis methods will be used for: (1) analysis of the centrifuge results as an equivalent prototype and as a bridge between the results and existing field case history data, (2) identification of anticipated important parameters and sensitivities for consideration in the centrifuge dynamic tests, (3) careful design of centrifuge dynamic tests to maximize the results and to obtain results from each test that are applicable to several of the objectives, (4) analyses of pre, during and post dynamic test conditions, (5) extrapolation and comparison of centrifuge test results to limit the number and extent of needed tests and (6) important assistance in the necessary understanding and definition of the physics of the mechanisms and processes being investigated.

Results from the work of other researchers studying residual strength, causes of liquefaction and flow of liquefied soil will be incorporated and collaboration will be made. However, this study is unique in that it addresses the fundamental effective-stress behavior and mechanisms of soil as it is in the process of liquefying and not just the end point of a liquefied state. The entire process of liquefaction and the controlling conditions are key to eventual accurate predictions of anticipated deformations; how much and where.

CONCLUSIONS

Discussions have been given in this paper concerning the research presently ongoing to investigate further the effects of liquefaction and better quantification of post-liquefaction effects. Results from centrifuge in-flight cone penetrometer testing were presented to quantify lateral spreading as a result of liquefaction. These results show that the cone penetrometer can be used in the centrifuge to model the field cone with comparable results. The effects of overconsolidation and pre-shaking have been presented for a 6 m thick deposit. These results are all incorporated into prediction charts of amount of ground surface lateral displacement versus corrected tip resistance. Discussions were also presented concerning research to further define the $K\sigma$ and $K\alpha$ terms currently used in the simplified liquefaction analysis procedures. These variables are not well defined and can led to serious consequences for design or remediation.

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