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SHEAR STRENGTH OF LIQUEFIED SOIL

Timothy D. Stark[1] M. ASCE, Scott M. Olson[2] S.M. ASCE, Steven L. Kramer[3] M. ASCE, and T. Leslie Youd[4] M. ASCE

ABSTRACT

A National Science Foundation sponsored workshop on the shear strength of liquefied soil was held at the University of Illinois at Urbana-Champaign on April 18-19, 1997. The workshop brought together approximately 25 leading researchers, consultants, and government engineers to discuss the important and controversial topic of the shear strength of liquefied soils. The workshop was organized to foster discussion in three main areas: theoretical and conceptual issues, laboratory and field measurement of the liquefied shear strength, and liquefied shear strength estimation from back-analysis of case histories. This paper presents a brief summary of the discussions of the workshop and the issues on which consensus were and were not reached. Specific consensus topics that were discussed at the workshop included terminology, laboratory versus field-based strength measurements, identification and characterization of field case histories, strength normalization using the initial vertical effective stress, fines content corrections/adjustments for field tests, re-evaluation of liquefaction case histories, and future research needs.

INTRODUCTION

Castro (1969) showed that after liquefaction, many sands retain some resistance to shear deformation. Several procedures have been developed to evaluate this shear strength, which has been referred to as the steady-state strength by Poulos et al. (1985), residual strength by Seed (1987), and critical strength by Stark and Mesri (1992). As discussed in a subsequent section, the workshop was unable to reach a consensus on terminology to describe the undrained shear strength at large strain of a loose, cohesionless soil. Therefore, for the purposes of this paper, the shear strength available to a loose, cohesionless soil that experiences undrained loading and a

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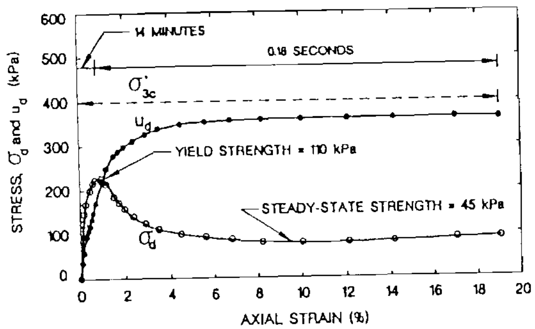

Figure 1. Stress-Strain Relationship from Isotropically Consolidated-Undrained Triaxial Compression Test on Loose Banding Sand (after Castro 1969)

subsequent loss of strength and stiffness at large strain will be referred to as the liquefied shear strength (or shear strength of liquefied soil). Clarification of the terminology is a subject of future research.

To clarify the shear strength of liquefied soil, Figure 1 illustrates the undrained behavior of a loose cohesionless soil using the results of an isotropically consolidated-undrained triaxial compression test conducted by Castro (1969). Casagrande (1936) first defined the shear strength mobilized at large strain while developing the "critical void ratio" concept. As a result, Stark and Mesri (1992) termed this shear strength the critical strength. Poulos (1981) termed this strength the steady-state shear strength (see Figure 1), which is the shear strength available in the steady state of deformation, where all particle orientation and breakage has occurred so that the soil continuously shears at a constant volume, constant effective normal stress, constant shear stress, and constant rate of shear strain. Seed (1987) referred to the shear strength of liquefied soil as the residual strength, as it represented the minimum strength available to liquefied sand during a flow failure.

EXISTING METHODOLOGIES

Poulos et al. (1985) developed a procedure for estimating the steady-state shear strength of liquefied soils using the results of monotonically loaded, consolidated-undrained triaxial compression tests with pore-water pressure measurements on undisturbed and reconstituted soil samples. The test results from reconstituted specimens are used to determine a relationship between undrained steady state shear strength and void ratio. This steady state line (SSL) is used to adjust the results of tests on undisturbed test specimens for densification during sampling, handling, transportation, laboratory preparation, and laboratory consolidation. This technique assumes that: (1) the slope of the SSL is the same for reconstituted and undisturbed samples, and (2) the slope of the SSL is independent of the method used to reconstitute the samples in the laboratory.

Seed (1987) presented an alternative approach for estimating the undrained shear strength of liquefied soils based on field case histories. This approach uses the liquefied residual strength back-calculated from case histories where Standard Penetration Test (SPT) results are available. The values of residual strength were back-calculated using limit equilibrium analyses, the final geometry of the slide mass, and different failure surfaces to determine a lower-bound residual shear strength. Seed and Harder (1990) used these data and a few additional case histories to develop a relationship between the residual shear strength mobilized during liquefaction flow failure and normalized equivalent clean sand blowcount, $(N_1)_{60\text{-}cs}$.

Stark and Mesri (1992) presented an approach for estimating the shear strength of liquefied soils as a function of the initial vertical effective stress. This approach is also based on the results of back-analysis of liquefaction case histories where values of the mobilized critical strength ratio were calculated for soil zones in which SPT results were available. The values of mobilized critical strength were back-calculated using the same procedure as Seed and Harder (1990). Stark and Mesri (1992) used these data to develop the relationship between the normalized critical strength mobilized during liquefaction flow failure and $(N_1)_{60\text{-}cs}$. This allows both the effects of soil grain characteristics (normalized blowcount) and the stress-dependent nature of the shear strength to be incorporated in stability analyses. Stark and Mesri (1992) also suggested that many of the liquefaction failures experienced drainage during flow, resulting in a back-calculated shear strength that did not represent an undrained critical state condition.

WORKSHOP FORMAT

The details of planning and organizing the workshop were coordinated by the steering committee of Timothy D. Stark, Steven L. Kramer, and T. Leslie Youd. Three discussion groups, (1) theoretical/conceptual issues, (2) shear strength estimation from laboratory and field testing, and (3) shear strength estimation from case histories were formed to facilitate discussions. One individual was appointed Discussion Group Leader and also Keynote Speaker for each group. At the beginning of the workshop, the Keynote Speakers presented a lecture describing the state-of-the-art, state-of-the-practice, main uncertainties, and the areas that warrant future research in their discussion area. The Keynote Speakers were:

Theoretical/Conceptual Issues	Professor Peter M. Byrne University of British Columbia
Shear Strength Estimation from Laboratory and Field Tests	Professor Geoffry R. Martin University of Southern California
Shear Strength Estimation from Case Histories	Dr. Gonzalo Castro GEI Consultants, Inc.

WORKSHOP DISCUSSIONS

After the keynote lectures, discussions were held during breakout sessions. The discussion groups consisted of approximately thirteen people per group to facilitate discussion and interaction. The discussion groups focused on specific topics during each session and the following paragraphs present each discussion topic and a brief summary of the discussions. The participants in each discussion group are listed in Appendix II.

Topic 1. Terminology for Liquefied Shear Strength – Discussed by the Theoretical/Conceptual Issues Discussion Group

The group discussed the terminology that should be used to describe the shear strength of liquefied soil, as well as the physical behavior controlling this shear strength and the observed phenomena. The observed phenomena include flow sliding and limited deformation (e.g., lateral spreads). The group concluded that these two phenomena should be considered and evaluated separately.

With regard to flow failure, the following terminology to describe the shear strength available to a soil after large strain were reviewed during the workshop:

- Steady State Strength (Poulos et al. 1985)
- Residual Strength (Seed 1987)
- Critical Strength (Stark and Mesri 1992)

The term 'undrained' was not included because it is unclear whether or not undrained conditions exist at all times during flow failures. The group commented that terminology is a difficult issue because of the controversy regarding the actual behavior of a soil during a liquefaction flow failure, i.e., whether or not a steady/critical state is reached, the effect of pore-water pressure redistribution, etc. Therefore, it was anticipated that a term that did not reflect any predisposition to laboratory tests would be preferable to describe the field behavior.

The term 'Apparent Flow Resistance' was presented to the workshop participants by the Theoretical/Conceptual Issues Discussion Group in a plenary session. Apparent flow resistance was defined as the available shear resistance during liquefaction flow failure, as influenced by boundary conditions, spatial variability, drainage or void redistribution, time or strain rate, and initial stresses. This term was anticipated to accommodate most, if not all, of the variability that exists in the field during flow failure, and does not restrict the observed shear strength to represent behavior observed in laboratory tests.

This term met considerable opposition in the plenary session. During discussion, the terms 'Apparent Residual Strength' and 'Mobilized Residual Strength' were proposed to describe the shear strength back-calculated from liquefaction flow failures. 'Apparent Residual Strength' received some endorsement. It was later proposed in the session that two different terms be used to describe the shear strength of liquefied soil. The term 'Apparent Residual Strength' may be reasonable to describe the shear strength back-calculated from liquefaction flow failures. The term 'Steady or Critical State Strength' could be used to describe laboratory shear strength where the steady/critical state is achieved. However, the terms shear strength of liquefied soil (used throughout this paper) and shear strength at large strain appear appropriate and more generic. The correlation or relationship

between the laboratory-estimated steady/critical state shear strength and the liquefied shear strength back-calculated from flow failures is a topic for future research.

Topic 2. Laboratory versus Field Determination (Preferred Test and Data Reduction) – Discussed by the Laboratory and Field Testing Discussion Group

All members agreed that field and laboratory testing for liquefaction studies should be complementary, not contentious. Further, the effort and complexity of the field and laboratory testing should be dependent upon the size and potential hazards of a project. A flow chart for guiding the methods of estimating liquefied shear strength is presented in Figure 2.

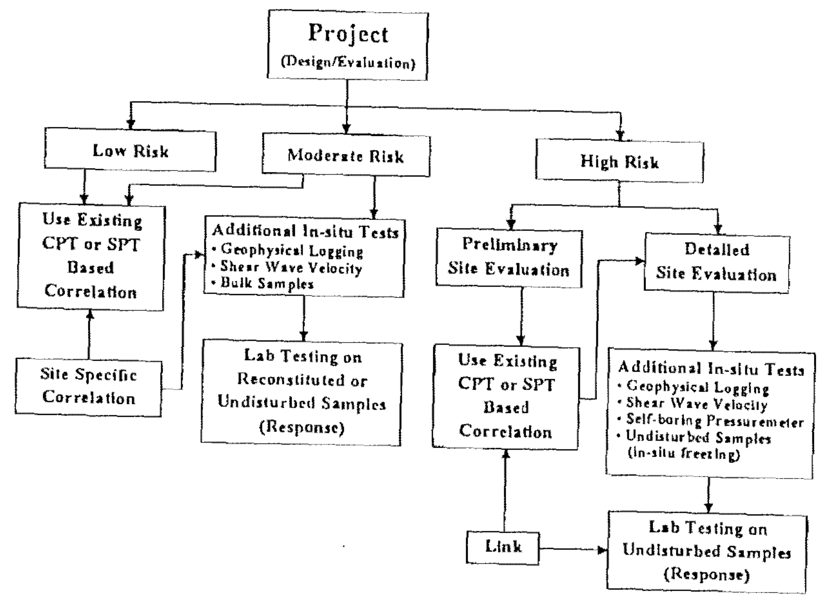

Figure 2. Flow Chart for Assessment of Shear Strength of Liquefied Soil (after Robertson, Workshop Presentation 1997)

<u>Field Testing</u>

The discussion of field testing focused on two objectives: (1) estimation of in-situ state leading to an estimate of the liquefied shear strength, and (2) direct estimation of the liquefied shear strength from field test results.

In-situ state is described by the effective stress and density of a soil prior to undrained loading. The state parameter is defined as the difference between in-situ void ratio and void ratio at the steady or critical state line at the in-situ effective stress. Void ratio can be estimated from undisturbed sampling (ground freezing, high-quality piston sampling, or test pit sampling), geophysical logging (gamma-gamma, borehole, or radio-isotope CPT), penetration testing (CPT or SPT), or shear wave velocity testing. All of these techniques are subject to various difficulties and/or uncertainties, all require knowledge of the position of the steady/critical state line (SSL/CSL), and some require values of e_{min} and e_{max}. The state parameter can be directly estimated using the CPT (Been et al. 1986) or self-boring pressuremeter test (Yu 1994), and does not require previous knowledge of e_{min}, e_{max}, and the position of the SSL/CSL.

Estimating the liquefied shear strength from field test results utilizes existing correlations where shear strength (or normalized shear strength) at large strain back-calculated from field case histories is related to a field test parameter such as penetration resistance. Correlations exist for the SPT (Seed and Harder 1990, Stark and Mesri 1992, Ishihara 1993), CPT (Olson and Stark 1998), shear wave velocity, V_s (Fear and Robertson 1995), and field vane test (undrained), FVTU (Charlie et al. 1995). Several concerns were expressed during the workshop regarding the use of existing correlations, including: (1) the effect (if any) of fines content, plasticity, mineralogy, and grain shape; (2) the appropriate value of test result, e.g., average, median, minimum, or other value; and (3) the reliability of the correlation itself because of the reliability of the case histories and the scatter of the correlation.

The group agreed that, despite uncertainties regarding the influence of fines content and possible thin layer effects, the CPT/CPTU/seismic CPTU represents an economical and reliable means for field testing. However, the SPT remains useful for verifying CPT results and/or investigating liquefaction resistance because of existing experience and correlations.

Laboratory Testing

Several issues, including sampling procedures, testing difficulties and interpretation, and applicability of centrifuge testing, were addressed regarding laboratory testing. The group discussed the relative merits and difficulties associated with 'undisturbed' sampling techniques including ground freezing (Yoshimi et al. 1989), large diameter sampling, and high-quality fixed piston sampling (Poulos et al. 1985). Ground freezing was considered by the group to be the preferred method to obtain 'undisturbed' samples, when project risk justifies the large cost. Large diameter sampling was considered appropriate only if the utmost care is used to obtain the sample. Fixed piston sampling was least preferred because of the lack of understanding of sampling, handling, and extruding procedures and because of the corrections required to estimate the in-situ void ratio from the sampled void ratio. However, the group expressed interest in this technique provided more documentation of sampling, handling, and extruding procedures is introduced into the literature.

Laboratory tests discussed include undrained triaxial compression and extension, simple shear, and torsional ring shear. No consensus was achieved because of the multitude of questions surrounding observed behavior in laboratory tests, including stress path effects, mode of shear effects, strain/displacement required to reach steady state, and whether existing test devices could attain this strain/displacement, sample preparation, significance of quasi-steady state strengths, etc. These are topics considered for future research.

Centrifuge testing (Fiegel and Kutter 1994) is model testing, not element testing, and therefore is subject to a different set of difficulties and concerns. In addition, the ability to generate large strains in the centrifuge test was questioned. Test results are limited, but indicate that the liquefied shear strength is not constant due to void ratio and pore-water pressure redistribution, and that boundary conditions are critical to test results. The group concluded that the use of the centrifuge for estimating the liquefied shear strength warranted further research.

Topic 3. Classification and Characterization of Liquefaction Field Case Histories – Discussed by the Case History Discussion Group

Classification of Liquefaction Field Case Histories

A common feature in liquefaction case histories is that a static driving shear stress, τ_d, was present prior to liquefaction, and that the direction of the permanent deformation is controlled by the direction of τ_d. As a consequence of these permanent deformations, the soil configuration changes and the magnitude of τ_d is reduced. It was suggested to classify case histories based upon the reduction of τ_d.

Category 1: Case histories in which the magnitude of τ_d is reduced by more than 10% when comparing the soil configuration before and after the liquefaction incident. This category covers flow slides of earth structures and/or their foundations, as well as the ground movement close to a free face in some lateral spreads. In this category, the permanent ground deformation is primarily driven by the static forces. Case histories applicable to this category include Lower San Fernando Dam, Fort Peck Dam, and Mochikoshi Tailing Dike 1.

Category 2: Case histories in which the magnitude of τ_d is reduced by 10% or less when comparing the soil configuration before and after the liquefaction incident. This category covers most of the ground movements in lateral spreads caused by earthquakes, as well as some case histories of limited deformations of earth structures and/or their foundations. In this category, inertia forces due to earthquake shaking play a major role in the deformations. Case histories applicable to this category include Upper San Fernando Dam, Heber Road, and Juvenile Hall.

The discussion group agreed that only Category 1 case histories will provide information on the liquefied shear strength. This strength does not necessarily control the development of limited strains under earthquake shaking (Category 2 case histories).

Characterization of Liquefaction Field Case Histories

The discussion group developed a list of the field data that should be obtained for back-analysis purposes and the importance of this information for flow slides and lateral spreads. Because of space constraints, this list is presented in the workshop proceedings (Stark et al. 1998).

Topic 4. Normalization with Initial Vertical Effective Stress – Discussed by the Theoretical/Conceptual Issues Discussion Group

The group began discussions with general acceptance of the concept of normalization of the liquefied shear strength. The stipulations to normalization are believed to be: (1) the SSL/CSL and the initial consolidation line (ICL) must be parallel, (2) the soil must be loose, i.e., contractive, (3) the soil must be deposited in a consistent manner, and (4) the soil must be subjected to a consistent stress history. For practical purposes, it is beneficial to correlate the normalized liquefied shear strength to a normalized penetration resistance. This allows both the effects of soil grain characteristics and the stress-dependent nature of the shear strength to be incorporated in stability analyses. However, it should be noted that if a sand is overconsolidated, normalization by the existing effective stress will lead to a conservative estimate of liquefied shear strength, and if case histories used to estimate the normalized shear strength involve overconsolidated sands (rather than normally consolidated sands, as is typically assumed), the normalized shear strength may be overestimated. These issues should be considered topics for future research.

In general, the group agreed that normalization was appropriate for compressible soils, such as silty sands and tailings sands. For compressible soils, the ICL is often parallel or nearly parallel to the SSL/CSL. For these cases, as effective confining stress increases, the value of state parameter remains nearly constant and for a given value of state parameter, the value of normalized liquefied shear strength is constant. The concept becomes uncertain for clean sands where the slope of both the ICL and SSL/CSL becomes small and may not be parallel. In these cases, the compressibility of the sand is critical. In light of these discussions, future research should consider the applicability of normalization, with emphasis on clean sands.

Topic 5. Fines Content Correction/Adjustment for Field Tests – Discussed by Field and Laboratory Testing Discussion Group

The fines content correction/adjustment is needed because penetration resistance is influenced by fines content (percent by weight passing the No. 200 sieve), soil compressibility, gradation, drainage, permeability, grain characteristics, age, overconsolidation, cementation, etc. Increased fines content is anticipated to lead to a more 'undrained' condition during penetration, resulting in a lower penetration resistance. Fines content is not the only variable that influences penetration resistance, but is an easily measured and quantifiable parameter to gage the effect of soil grain characteristics on penetration resistance. Therefore, liquefaction resistance relationships that separate liquefaction from non-liquefaction case histories use fines content and/or D_{50} to separate soil types. From these relationships, increasing fines content leads to an increase in the fines content correction for penetration resistance.

The main question addressed by the discussion group was: Can the fines content correction/adjustment developed from field case histories of liquefaction and non-liquefaction be used in the estimation of the liquefied shear strength from case histories of liquefaction flow failures? The group concluded that a universal correction was uncertain, because fines content is not the only parameter that affects penetration resistance and the liquefied shear strength. It was concluded that available case histories are inadequate to clarify the issue and additional research should be conducted on this topic.

The CPT shows promise as a means of estimating the normalized liquefied shear strength without relying on a fines content (or any other) correction/adjustment. Ongoing research is attempting to relate normalized liquefied shear strength to a soil behavior index (Robertson, Workshop Presentation 1997). The soil behavior index (Robertson and Fear 1996) is a function of both normalized CPT tip resistance and normalized CPT friction ratio. At this time, it is uncertain as to whether normalized friction ratio or normalized sleeve friction is the more appropriate parameter, but the logic is to remove the fines content correction/adjustment from the procedure. In this fashion, the CPT becomes a stand-alone tool, and the SPT can be used as an independent verification of the CPT results.

Application of a fines content correction/adjustment can lead to invalid and potentially unconservative results. At this time, there is insufficient field or laboratory data to corroborate the correction and additional research is warranted. However, existing fines content corrections/adjustments related to a specific method for estimating the liquefied shear strength should be used.

Topic 6. Re-Evaluation of Liquefaction Field Case Histories – Discussed by the Case Histories Discussion Group

It was agreed that re-evaluation of existing field case histories was appropriate given the current state of knowledge and the availability of new information for some of the cases. However, re-evaluation should include some or all of the following items.

If pertinent information is available, the re-evaluation should consider momentum effects on the shear strength developed along the failure surface. Typically it is anticipated that using the pre-failure geometry to back-calculate the liquefied shear strength will result in an unconservative estimate and using the post-failure geometry results in a conservative estimate. During a liquefaction flow failure, the driving stresses initially are larger than the liquefied shear strength, which results in acceleration of the soil mass. The sliding mass therefore continues to move and deform even after the geometry is such that driving stresses are equal to the resisting strengths. It was suggested that the average geometry (between pre-failure and post-failure) might be appropriate to re-evaluate the liquefied shear strength if information to evaluate momentum effects is not available (Castro, Workshop Presentation 1997).

The effect (if any) of fines content (and other parameters such as aging) on penetration resistance and soil drainage is also of importance. It is anticipated that a lower fines content will result in more drainage. The fact that the liquefied shear strength (or normalized strength) is correlated to penetration resistance requires that the investigator consider these effects. If a fines content correction/adjustment is too large, the estimated liquefied shear strength may be unconservative.

The re-evaluation must analyze the proper failure mechanism and soil behavior. For example, flow failures and lateral spreads should not be analyzed using the same technique. These failures result from different mechanisms, and the strengths mobilized during each failure may not be the same. The case histories for re-evaluation should be divided into categories as described above, namely, flow failures and limited deformations. Limited deformations can be further subdivided into lateral spreads (where driving stresses are relatively low, e.g., Juvenile Hall), and other cases (where driving stresses are large, e.g., Upper San Fernando Dam).

Topic 7. Future Research Needs on Liquefied Shear Strength of Granular Soils – Discussed by all Participants

Research needs with respect to theoretical/conceptual issues, field and laboratory tests, and liquefaction case histories were identified and discussed by the workshop participants during a plenary session. A complete listing of the research needs can be found in the workshop proceedings (Stark et al. 1998). An abbreviated list is presented in the conclusions.

CONCLUSIONS

A National Science Foundation sponsored workshop on the shear strength of liquefied soil was held at the University of Illinois at Urbana-Champaign on April 18-19, 1997. The workshop was organized to foster discussion in three main areas: theoretical and conceptual issues, laboratory and field measurement of the liquefied shear strength, and liquefied shear strength estimation from field case histories. An important function of the workshop was to identify areas of future research. Some of these areas are presented below, along with some recommendations and conclusions.

Some of the theoretical/conceptual topics for future research are: (1) the appropriateness of normalization of the liquefied shear strength, (2) understanding the physical mechanisms that control lateral spreading, (3) investigating the effect of the state parameter on large strain behavior, and (4) gaining consensus on terminology. With respect to field and laboratory testing, some of the future research topics include: (1) improved sampling and laboratory testing techniques to evaluate the shear strength of liquefied soil, (2) investigating the effect of grain characteristics on field test results, and (3) applicability of centrifuge testing to estimate the shear strength of liquefied soil. Some of the topics for future research on field case histories include: (1) re-evaluation of field case histories, (2) obtain a consensus on input parameters and back-calculated shear strengths, (3) evaluate the effect of fines content, drainage, and mixing during flow or spreading, and (4) understand the mechanism(s) that control lateral spreading. Lastly, augmentation of case histories of flow slides using physical models, full-size field tests, and instrumentation of existing sites that are likely to experience some static or seismic liquefaction should be undertaken.

The terms 'apparent residual strength' and 'steady/critical state strength' were proposed to describe the shear strength back-calculated from field case histories and laboratory test results, respectively. However, the terms shear strength of liquefied soil (used throughout this paper) and shear strength at large strain appear appropriate and more generic. The CPT represents an economical and reliable means for estimating the shear strength of liquefied soil. Normalization of the liquefied shear strength is appropriate for most silty soils, but may not be appropriate for some clean sands. Given the current state of knowledge, it is recommended that liquefaction flow failures and lateral spreads be re-evaluated. However, the shear strength back-calculated from case histories of these two phenomena should be considered and evaluated separately.

ACKNOWLEDGMENTS

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APPENDIX II. LIST OF WORKSHOP PARTICIPANTS

Theoretical/Conceptual Issues Discussion Group

- Peter M. Byrne, University of British Columbia, Keynote Speaker
- J. David Frost, Georgia Institute of Technology
- Marte Gutierrez, Norwegian Geotechnical Institute
- Richard M. Iverson, U.S. Geological Survey
- Michael G. Jeffries, Golder Associates, Inc.
- Joseph P. Koester, U.S. Army Corps of Engineers, Waterway Experiment Station
- Steven L. Kramer, University of Washington
- Jean H. Prévost, Princeton University

Shear Strength from Laboratory and Field Tests Discussion Group

- Wayne A. Charlie, Colorado State University
- Pedro A. de Alba, University of New Hampshire
- Bruce L. Kutter, University of California at Davis
- Geoffery R. Martin, University of Southern California, Keynote Speaker
- Gholamreza Mesri, University of Illinois at Urbana-Champaign
- Scott M. Olson, University of Illinois, formerly Woodward-Clyde Consultants
- Steve J. Poulos, GEI Consultants, Inc.
- Michael F. Riemer, University of California at Davis
- Peter K. Robertson, University of Alberta

Shear Strength from Case Histories Discussion Group

- Gonzalo Castro, GEI Consultants, Inc., Keynote Speaker
- Ricardo Dobry, Renesselar Polytechnic Institute
- A. Gus Franklin, U.S. Army Corps of Engineers, Waterways Experiment Station
- David R. Gillette, U.S. Bureau of Reclamation
- Leslie F. Harder, Jr., California Department of Water Resources
- John C. Horne, Clemson University
- I.M. Idriss, University of California at Davis
- Timothy D. Stark, University of Illinois

CPT BASED LIQUEFACTION RESISTANCE OF SANDY SOILS

Scott M. Olson[1], S.M. ASCE and Timothy D. Stark[2], M. ASCE

ABSTRACT

Stark and Olson (1995) compiled 180 field case histories of liquefaction and non-liquefaction to develop relationships between liquefaction resistance and corrected CPT tip resistance. In developing some of these case histories, more than one elevation within a single sounding was evaluated. Herein, these case histories have been re-evaluated so that one sounding provides only one case history, reducing the original database to 80 cases. Furthermore, 92 additional case histories of liquefaction and non-liquefaction have been added to the revised database. The revised database now contains 172 independent field case histories of liquefaction and non-liquefaction, and confirms the liquefaction resistance relationships proposed by Stark and Olson (1995). This study also concludes that the procedure of utilizing more than one elevation within a single sounding for evaluating liquefaction resistance is justified. This practice is especially applicable to CPT soundings that penetrate deposits of significantly different geologic age.

INTRODUCTION

Peck (1979) indicated that because of difficulties in understanding and modeling all of the factors that affect the liquefaction resistance of a soil, in-situ penetration testing is the preferred method to estimate liquefaction resistance. In-situ penetration testing includes the cone penetration test (CPT) and the standard penetration test (SPT). The cone penetration test offers several advantages over the standard penetration test including better standardization, precision and accuracy, improved cost-effectiveness, and it provides a nearly continuous record of penetration resistance throughout a soil deposit. For these reasons, the cone penetration test has seen increasing popularity and use for liquefaction assessment. However, the SPT allows a sample to be obtained for gradation purposes and allows verification of liquefaction resistance using existing correlations.

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