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by

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(ABSTRACT)

Liquefaction is a phenomenon where a saturated soil can temporarily lose its shear strength during an earthquake as a result of the development of excess pore pressures. For the past 25 years since liquefaction phenomenon was first explained, it was thought to be mainly a problem with clean sand, and most of the research has focused on these soils. However, as case history information has come to light, it has become apparent that silty sands are commonly involved, and in some cases even silts. This has generated a need for knowledge about the response of silty sands and silts under seismic loading. Related to this issue is the question of how best to determine the liquefaction resistance of these soils in a practical setting.

This research has the objectives of providing an understanding of the behavior of saturated silty sands under seismic loading, and developing a rational basis for the use of the Cone Penetration Test (CPT) to predict liquefaction resistance in these materials. The study is primarily experimental, relying on laboratory and field testing and the use of a unique, large scale calibration chamber. The calibration chamber allows the field environment to be duplicated in the laboratory where conditions can be closely controlled and accurately defined.

One of the first problems to be overcome in the research was to determine how to prepare specimens of silty sands that would reasonably duplicate field conditions in both the small

scale of the conventional laboratory tests, and the large scale of the calibration chamber. Out of four different methods explored, consolidation from a slurry proved to be best. Two silty sands were located which had the desired characteristics for the study. Field work, involving both the Standard Penetration Test (SPT) and CPT was done as part of this investigation. The behavior of the silty sands were determined in the laboratory from monotonic and cyclic loading tests.

The test results show that the effect of fines is to reduce the cone penetration resistance, but not to affect the liquefaction resistance. The steady state shear strength of the soils seems to be correlated to the cone tip resistance, however, this correlation shows a higher steady state shear strength than those back figured from case history data. The results were also used to define state parameters for both of the soils tested. The state parameter was found to be a reliable index to the liquefaction potential and further study in this area is recomended.

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INTRODUCTION

During the past twenty years, research in geotechnical engineering has amply demonstrated that seismic shaking can induce excess pore pressures in saturated sands. This pore pressure development leads to a reduction of the stiffness and strength of the sand, and in extreme, it can cause the soil to liquefy. Liquefaction is a condition where the soil can flow in the presence of shear stresses such as those induced by a slope, a building foundation, or an embankment. Where the subsurface conditions are optimal for liquefaction, this phenomenon can account for a significant percentage of the life and property loss that occurs in an earthquake.

To this date (1989), most investigations into liquefaction have focussed on clean sandy soils. In part, this was due to a natural tendency to work with the simplest materials to avoid complications in testing. This trend also reflected the fact that few field studies were available to document the kinds of soils involved in liquefaction events. With time, evidence has grown that liquefaction is often associated with silty sands, and in some cases silts (Andresen and Bjerrum, 1967; Dobry et al., 1967; Lee et al., 1975; Youd and Bennett, 1983; Zhou, 1981; Ishihara et al., 1984; Hsing and Seed, 1988). As a result more interest has developed in the response of saturated silty sand during seismic loading (Ishihara et al., 1978; Chang et al., 1982; Dezfulian, 1984; and Kuerbis et al., 1988). In the 1985 National Research Council workshop on liquefaction, one of the priority research needs was identified as understanding the behavior of silty sands and silts (National Research Council, 1985).

In addition to the change in attitudes about silty soils, the past decade has seen a shift in views about the methods of testing that should be used to identify liquefaction resistance of soils. The general conclusion has been that while laboratory tests are useful in research studies, it is not possible to reproduce the vagaries of soil structure and stress history in the laboratory that exist in the field. Thus, there has been a move towards field testing as the preferred method to evaluate the resistance of soil to seismic loading. In this process, the early emphasis was placed on use of the Standard Penetration Test (SPT) to provide the data base to characterize the soil (Seed, 1979; Tokimatsu and Yoshimi, 1983). The SPT is a simple procedure, and is commonly done as a matter of course in most geotechnical investigations. Also, because the SPT has been around for a long time, data were often available for sites where behavior was documented under earthquake shaking (Ishihara, 1977; Seed and Idriss, 1981; Seed et al., 1983). Recently, it has been recognized that the cone penetration test (CPT) offers a number of advantages over the SPT for soil characterization and for help in quantifying liquefaction resistance (Zhou, 1980, 1981; Robertson and Campanella, 1985; Ishihara, 1985; Seed and de Alba, 1986; Shibata and Terapaksa, 1987). However, the data base supporting the CPT is limited, and few, if any, formal calibration studies have been conducted in silty sands.

The purpose of this investigation is to improve our knowledge about the undrained behavior of silty sands under cyclic loading, and to help formulate a technology for use of the cone penetrometer in quantifying the liquefaction resistance of silty sands. The basis of the study is experimental, relying on laboratory and field testing, and full-scale cone penetration tests in a unique large calibration chamber.

The first cone penetrometers were developed in the Netherlands to determine the soil parameters needed to define the resistance of piles in clays. Since then, this device has been extended to a wide range of applications. A modern cone operates electrically (Figure 1.1), and records the resistance at the tip, and friction acting on the sleeve of the cone. According to ASTM standards, the cone is 35.7 mm in diameter, with a cone tip angle of 60°, a projected tip area of 10 cm^2 , and a friction sleeve surface area of 150 cm^2. Recently smaller and larger cones than the standard have been proposed and are used in practice.

The use of the cone penetrometer in liquefaction studies has taken a number of different paths, most of which are based on empirical correlations related to past site performance in earthquakes (Zhou, 1980, 1981; Shibata and Terapaksa, 1987, 1988). In these methods, the cone information is often supplemented by SPT data converted to equivalent cone tip resistances using empirical factors. Such data are useful, but ultimately are questionable because of the scatter in the conversion relations. A recent development is the introduction of concept using a soil resistance known as the "undrained steady state shear strength," and a "state parameter". The undrained steady state shear strength is the resistance of the soil when it reaches what is known as the critical state, following failure and application of large strains (Poulos et al., 1985). The state parameter defines the degree by which the initial conditions of the soil deviates from the critical state, and it has been correlated with cone tip resistance (Been et al., 1987a; Jefferies, 1988). In this research, the state parameter is used to characterize the behavior of silty sands under seismic loading.

In addressing the issues related to the use of the cone penetrometer to identify liquefaction resistance, the objectives were to :

1.) determine a reliable and repeatable method to produce samples of silty sand for both small samples in laboratory tests and the large samples used in the Virginia Tech large scale calibration chamber that are as representative as possible of field conditions.
2.) perform static and cyclic laboratory tests to define parameters and behavior of the silty sands that relate to development of excess pore pressure in an earthquake.
3.) conduct cone penetration tests in silty sands in both the field and in the large scale calibration chamber to provide well documented data base for cone resistance in these

materials.

4.) Using the data from this investigation, improve the methods for predicting liquefaction resistance of silty sands both from a conceptual and practical standpoint.

Two silty sands were used for the test program, the first of which was obtained from the location of the old Pepper's Ferry on the New River near Blacksburg. A field investigation using CPT and SPT procedures was performed at this site. The second soil came from the excavation for Yatesville Dam in Kentucky, and was provided by the U.S. Corps of Engineers. This material was used in the calibration chamber tests. In the course of this research, four procedures were examined to assess the sample formation issue. This work involved both small scale tests in the laboratory and full scale tests in the calibration chamber. To define the pore pressure and strength response of the silty sands, a total of 15 monotonic triaxial tests and 42 cyclic triaxial tests were conducted.

The calibration chamber tests involved excavating and replacing 6000 kg of the Yatesville soil for each test. To prepare the Yatesville sand for testing, it had to be processed to eliminate oversize particles and detritus. After processing, the soil was placed in the chamber in a slurry form, and consolidated for two to three weeks under stresses similar to those in the field conditions and also used in the small scale laboratory tests. A total of five calibration chamber specimens were created and 23 CPT's were performed.

The results of the investigation are provided in the following chapters. Chapter 2 gives a background review of previous work on liquefaction evaluation and cone penetration testing related to this study. At the end of this chapter the justifications for this work are presented. The scope and general methods used in the investigation are given in Chapter 3, along with a description of the two field site and testing programs at the sites. Chapter 4 covers the studies performed concerning sample fabrication techniques. This effort turned out to be more difficult than originally thought in that well developed procedures for clean sands did not work for silty sands. It is believed that the results have implications important for a variety

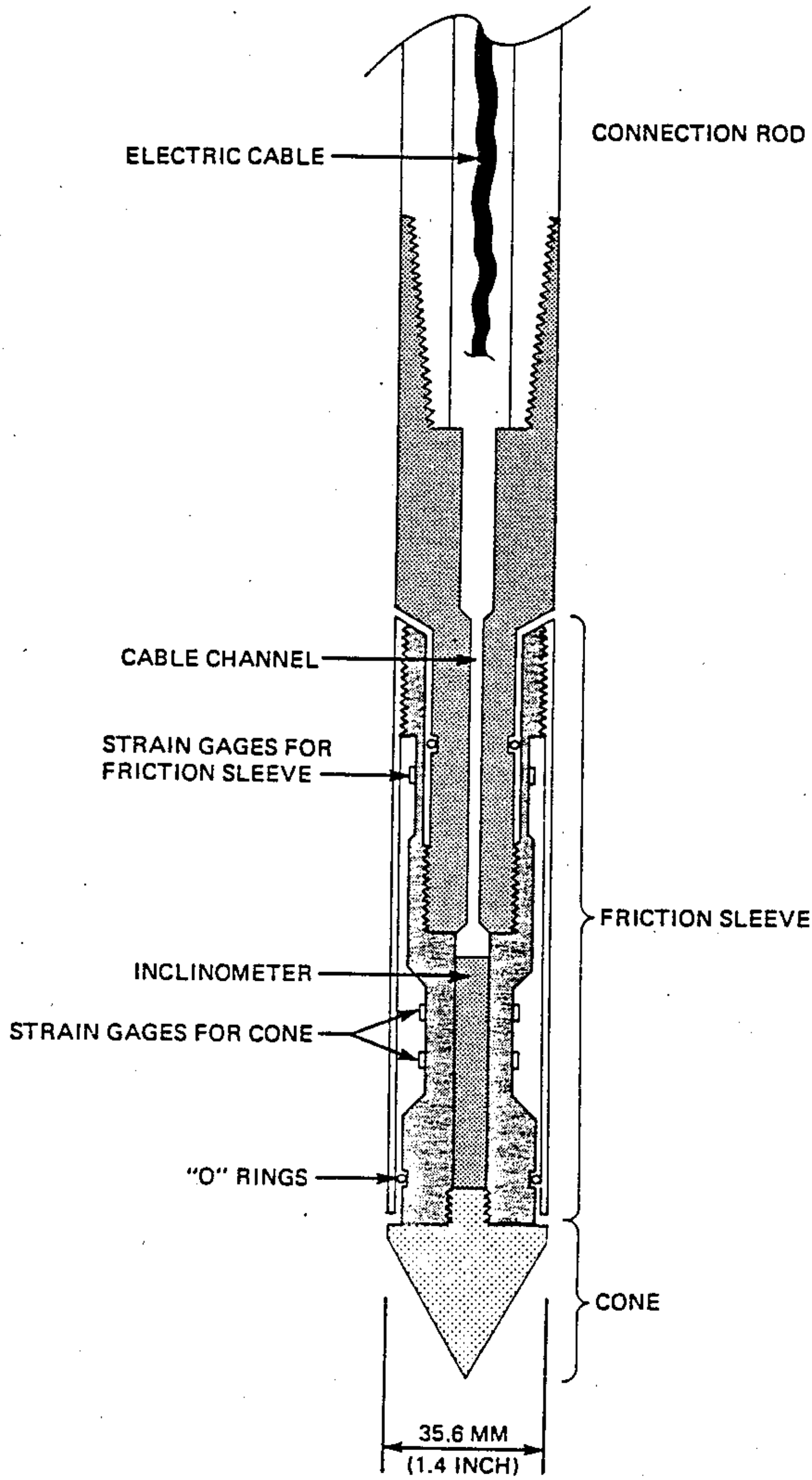

FIG.1.1. ELECTRICAL CONE PENETROMETER

of laboratory studies using silty sands. The findings obtained in the laboratory triaxial tests are presented in Chapter 5. Basic data for defining the state parameter for the two test sands is given, and compared to those for similar soils reported in the literature. Chapter 6 presents the results of the cone penetration testing in the calibration chamber. These data are unique in that the cone results can be interpreted in terms of well defined soil densities and stress conditions. The test results in the calibration chamber will be compared to the penetration characteristic in the field where the soil was derived. The field testing effort at the Pepper's Ferry site is covered in chapter 7, and the results are related to those obtained on the Peppers' Ferry soil in the other types of tests. Chapter 8 links the findings of the entire experimental program, and presents a new procedure for evaluating the liquefaction resistance of silty sands using a cone penetrometer. Finally Chapter 9 gives the summary and conclusions.