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Use of explosives to investigate liquefaction resistance of aged sand deposits

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A B S T R A C T

Current methods of predicting liquefaction potential were largely developed using data from relatively young deposits or deposits that have been frequently disturbed (i.e., areas of high seismicity). While engineers recognize that these prediction methods are overly conservative for assessing liquefaction potential in geologically aged deposits, there is no widely accepted method for quantitatively accounting for age in these assessments. Because a major disturbance, such as an earthquake or explosion that causes liquefaction, resets a deposit's "geological age," data from explosive compaction projects in aged deposits are used herein to provide information about both the aged and fresh deposits. A recent explosive compaction project performed in Griffin, IN, as well as four other explosive compaction projects, is used to develop an aging correction relationship for liquefaction resistance. Using a log-linear trend frequently proposed in previous studies, the method proposed herein predicts an approximate 20% gain in liquefaction resistance per time log cycle. The proposed relationship can be used directly if the time since deposition or last disturbance is known or in conjunction with the measured-to-estimated-velocity-ratio (*MEVR*) relationship proposed by Andrus et al. if the deposit's age is unknown.

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1. Introduction

This paper presents a model for predicting the liquefaction resistance of aged sands. The model utilizes in situ test data from previous and new studies in which explosives were used to disturb soil deposits of various ages. Whitman (1971) and Seed and Idriss (1971) developed the "simplified" procedure to evaluate the liquefaction potential of soil deposits using the standard penetration test (SPT). Procedures have since been developed for other in situ tests, including the cone penetration test (CPT) (e.g., Robertson and Wride, 1998; Moss et al., 2006; Idriss and Boulanger, 2008) and small strain shear wave velocity (V_s) (e.g., Andrus and Stokoe, 2000; Kayen et al., 2013). The majority of the liquefaction and non-liquefaction case histories used to develop these procedures are for late Holocene aged (~12,000 years ago to the present) deposits (Youd et al., 2001). Many investigators (Ohsaki, 1969; Casagrande, 1976; Youd and Perkins, 1978; Seed, 1979) noted increased liquefaction resistance in Pleistocene aged (between 2,500,000 and 12,000 years ago) deposits, demonstrating that current liquefaction prediction methods are overly-conservative in Pleistocene deposits.

Andrus et al. (2009) found that large disturbances can negate the benefits of geologic age to liquefaction resistance by returning the soil to a freshly deposited state. Explosive compaction (blast-densification) projects in aged deposits can provide insight into such disturbance and subsequent aging of sands. Specifically, results from in situ tests performed prior to explosive compaction reflect the aged state of the soil, while the results from tests conducted within days of explosive compaction reflect a freshly deposited state.

This paper summarizes previous work in the area of liquefaction resistance of aged deposits. Explosive compaction projects conducted in aged deposits are then described. In situ test results from these studies are used to estimate increase in liquefaction resistance with age. The data is analyzed using a consistent procedure (Idriss and Boulanger, 2008) to enlarge the database of age correction factors. Finally, a new method of accounting for age in determining liquefaction resistance is proposed.

2. Background

Seed (1979) proposed an early method of accounting for geologic aging on liquefaction resistance. He presented results from cyclic triaxial tests performed on Monterey No. 0 sand. The samples were prepared to a relative density of 50% and consolidated under an effective confining stress of 155 kPa for different time periods. A 12% increase in liquefaction resistance was observed for the samples aged for 10 days and a 25% increase was observed for samples aged for 100 days. This data was compared to the results of tests performed on undisturbed

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specimens. Seed concluded that the liquefaction resistance of natural deposits might be as much as 75% greater than that of freshly deposited laboratory specimens. Skempton (1986) and Kulhawy and Mayne (1990) documented an increase in SPT blow count with geologic age for deposits having similar relative densities (D_r). Lewis et al. (1999) used data from sites with geologic ages between 85,000 and 125,000 years that liquefied during the 1886 Charleston, SC, earthquake. In conjunction with estimates of the accelerations at the sites and the magnitude of the 1886 event, Lewis et al. (1999) drew a lower bound curve of the cyclic resistance ratio as a function of SPT N-value corrected to 60% hammer energy and one atmosphere of confining pressure. Comparing this curve with the Seed et al. (1984) liquefaction triggering curve, a strength gain ratio was calculated. Arango et al. (2000) used this data, as well as other data gathered by Arango and Migues (1996), Bechtel (1993), and Bechtel (1995), to extend the trend developed by Seed (1979) for deposits older than 3000 years.

Lewis et al. (2004) compared SPT and CPT results from aged deposits at the Savannah River Site, SC, to cyclic triaxial test results from "undisturbed" samples from the same site. Observing that truly undisturbed sampling is impossible, Lewis et al. (2004) point out that sample disturbance would lessen the effects of age, thereby decreasing the soil's cyclic strength. Accordingly, such laboratory testing would result in a conservative estimate of strength gain due to aging. Lewis et al. (2004) did not propose a relationship predicting the benefits of aging, but rather, provided additional evidence of time-dependent strength gain.

Leon et al. (2006) proposed a method to account for aging on liquefaction potential that entails using separate age corrections for in situ test data and for laboratory-determined cyclic resistance ratio (*CRR*) of the soil. The basis for this is their hypothesis that aging does not influence in situ test indices proportionally to its increase in *CRR*. They corrected the measured SPT N-values of aged deposits using the relationship proposed by Kulhawy and Mayne (1990). Using these age-corrected N-values, they estimate *CRR* for the soil as per Youd et al. (2001). This *CRR* was then adjusted for aging using the Arango et al. (2000) method. The age-corrected *CRR* and original in situ test results are then used to create a liquefaction prediction curve for aged deposits. This relationship was used in a paleoliquefaction study in South Carolina.

Monaco and Marchetti (2007) presented results of seismic dilatometer tests (SDMT). They showed that V_s and dilatometer (DMT) horizontal stress index (K_D) and dilatometer modulus (E_D) yield different predictions of *CRR* and provide several explanations for the differences. First, they suggested that the larger strains induced during DMT testing more closely relate to earthquake induced strains than the strains associated with seismic wave propagation used to obtain V_s. Similarly, they advised that DMT results correlate better to D_r than to V_s. However, the results of DMT, CPT, and V_s testing conducted by Saftner et al. (2011) in Griffin, IN and New Madrid, MO showed that DMT results predict low *CRR* values compared to CPT results. Destruction of the geologic aging benefits during penetration of the DMT blade prior to taking the DMT readings would explain this behavior. Therefore, DMT K_D may not be as sensitive to geologic aging as CPT tip resistance (q_c).

Lewis et al. (2008) used cyclic triaxial test data for aged samples from previous studies to scale the Idriss and Boulanger (2004) CPT-based *CRR* curves for evaluating liquefaction potential of aged deposits. They compared their results with those from other studies (Fig. 1). In this figure, the Strength Gain Factor, K_{DR}, is the ratio of the *CRR* of the aged soils to the *CRR* of freshly deposited soils. Lewis et al. (2008) proposed Kulhawy and Mayne's (1990) relationship as a lower bound for K_{DR} and scaled this relationship to form an upper bound.

Hayati and Andrus (2009) updated the K_{DR} relationship originally proposed by Andrus et al. (2009):

$$K_{DR} = 0.13\ \log_{10}(t) + 0.83 \tag{1}$$

where t is the age of the deposit (or time since last major disturbance) in years. In lieu of using time directly, Andrus et al. (2009) proposed that the ratio between measured and estimated V_s (*MEVR*) is an accurate proxy for deposit age. Estimated V_s was determined using empirical correlations between V_s and SPT/CPT results. Older deposits show higher measured V_s than younger deposits with similar q_c. They recommended Eq. (2) for relating the *MEVR* to age of deposit.

$$MEVR = 0.0820\ \log_{10}(t) + 0.935 \tag{2}$$

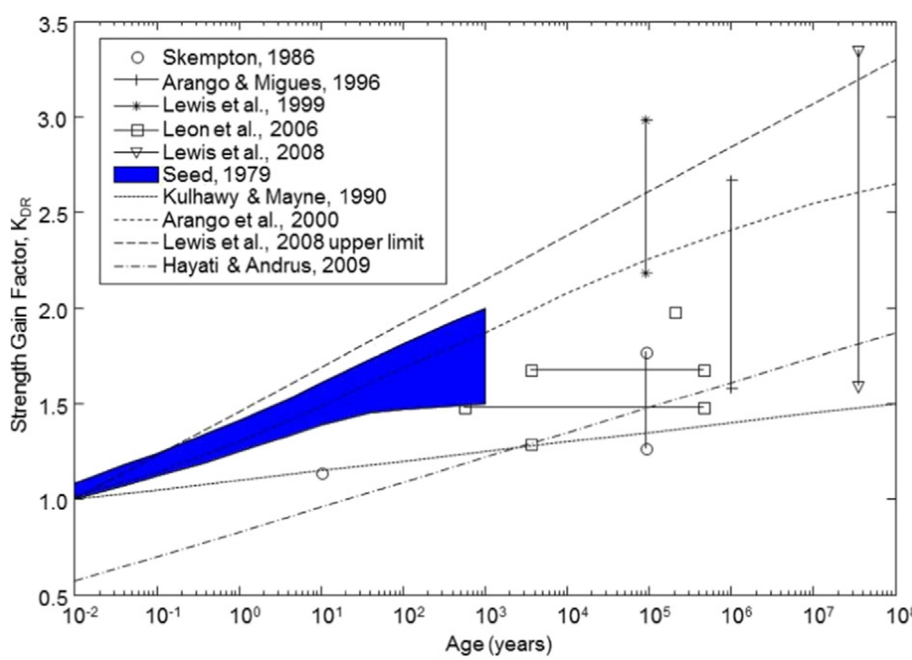

Fig. 1. Ratio of aged to fresh cyclic resistance ratio in aged sand deposits and proposed predictive relationships (adapted from Arango et al., 2000).

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