Influence of Confining Stress on Liquefaction Resistance

by

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ABSTRACT

The confining stress factor K_σ is used in liquefaction evaluations to extend empirical charts for liquefaction resistance to confining stresses higher than the empirical field-performance database, approximately 1 atm (100 KPa). Estimates of K_σ from Harder (1988), Hynes (1988), Olsen (1984, 1994, 1996) indicated relatively large reductions in liquefaction resistance ratios with increasing confining stress. Laboratory work by Vaid and colleagues (1985, 1995) indicated higher values of K_σ. In this study, a database was developed to investigate the reasons for the broad scatter in K_σ. From our study we conclude that: 1) K_σ is strongly influenced by method of deposition, stress history, aging effects, and density; 2) reconstructed, pluviated specimens in the laboratory may represent recently deposited dredged materials or recently liquefied materials; however, 3) high quality undisturbed samples are needed to determine field-relevant values of K_σ. The MCEER International Liquefaction Committee (Youd & Idriss 1997) adopted the K_σ recommendations from this study.

KEYWORDS: Liquefaction, confining stress effects, gravels, stress focus, K sigma, earth dams, laboratory testing, stress history, pluviation.

1. BACKGROUND

Laboratory measurements typically indicate that for a given soil, consistency (relative density for sands and gravels) and stress history, there is a non-linear relationship between liquefaction resistance and confining stress (Seed & Idriss 1981; Seed 1983; Vaid et al. 1985; Hynes 1988; Harder 1988; Seed & Harder 1990; Pillai & Byrne 1994; Youd & Idriss 1997). Consequently, if cyclic strengths, either from laboratory measurements performed at a confining stress of 1 atm or estimated from correlations to in situ measurements such as Standard Penetration Tests (SPT), are linearly extrapolated to higher effective confining stress levels, the calculated liquefaction resistances may be too high. The effect of confining stress on liquefaction resistance is further complicated by soil compressibility and stress history.

The state-of-the-practice approach to account for the non-linear relationship between liquefaction resistance and vertical effective stress is to use published charts derived from existing laboratory data on similar materials or to determine a site specific relationship with a comprehensive laboratory testing program. Whichever approach is used, liquefaction resistance is conventionally represented as the Cyclic Resistance Ratio (CRR, the ratio of cyclic shear strength (τ_{cy}) divided by the vertical effective stress, (σ_v')). For a given soil at a given consistency and stress history, the CRR generally decreases with increasing vertical effective stress. This decrease is described by the factor K_σ which is defined as the ratio of CRR for a given σ_v' to the CRR at a vertical effective stress of 1 atm, CRR_1 (compared at the same relative density).

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The use of laboratory tests to establish CRR_1 for a material has decreased over the last decade in favor of in situ test correlations because of the cost-effectiveness of in situ measurements, the robustness of the Seed SPT-liquefaction chart (Seed et al. 1985, Youd & Idriss 1998), and concerns over sample disturbance and other issues associated with laboratory test results. The CRR_1 can be determined from in situ measurements such as the SPT, Cone Penetration Test (CPT), or shear wave velocity (V_s), or from laboratory measurements. The state-of-the-art for estimating CRR_1 using the SPT is given by Seed et al. (1985); using the CPT is given by Stark et al. (1995), Olsen et al. (1996), or Robertson & Wride (in Youd & Idriss 1997); and using V_s is given by Andrus & Stokoe (in Youd & Idriss 1997).

The database for these CRR_1 correlations consists of information from water-laid deposits of sands and silty sands, level to slightly sloping ground, under vertical effective stresses of less than 3 atm.

Consequently, laboratory tests have been used to provide a relative scale to adjust the CRR_1 values from in situ tests to higher confining stress levels and non-level ground stress conditions. The purpose of this study was to review the current state of knowledge with respect to the influence of overburden stress on liquefaction resistance. An emerging concept will be presented, namely the Stress Focus theory (Olsen 1994), which provides an alternative framework for interpreting confining stress effects on in situ measurements such as penetration resistance, and soil properties such as liquefaction resistance.

2. HISTORICAL K_σ DATA AND CHARTS

2.1 *K_σ Data and Charts*

Cyclic laboratory tests provide a means of determining liquefaction resistance of a soil under various controlled conditions--density, confining stress, stress history, applied cyclic load or strain history, and drainage boundary conditions. The influence of confining stress can be evaluated by conducting cyclic laboratory tests for a soil, holding the other parameters constant, at several confining stress levels. In this section, historical cyclic laboratory test data for a variety of soils are examined to observe trends in K_σ from the historical database.

Early tests on sands and silty sands indicated considerable scatter in the values of K_σ. These data, summarized in Figure 1 and taken in part from Harder (1988), include Upper and Lower San Fernando Dams (Seed et al. 1973, Seed et al. 1989) and Fort Peck Dam (Marcuson & Krinitzsky 1976). Superimposed on Figure 1 is an early K_σ relationship suggested by Seed (1983). As more data became available, the K_σ chart was updated by Harder (1988), and again by Seed & Harder (1990).

Olsen (1984) generalized the data trends from the preliminary K_σ relationship by Seed (1983), together with project data at WES into the following expression: $K_\sigma=(\sigma'_v)^{f-1}$. This expression is plotted in Figure 1. Olsen (1984) reported that the stress exponent, f, ranged from 0.6 to 0.95 with 0.7 recommended for sands. This recommendation is similar to the updated Seed curves shown in Figure 1.

Gravel data from Oroville Dam (Banerjee et al. 1979) and WES project files (Ririe, Folsom and Success Dams) were added to the database; these data are from large-scale cyclic triaxial tests on moist-compacted specimens. Silt, silty sand and sandy silt data was added from a number of dam studies, notably Upper and Lower San Fernando, Fort Peck, Enid and Arcadia Dams.

Byrne & Harder (1991) selected K_σ values for clean sands from previous work to develop a recommendation for the clean sands and gravels present at Terzahgi Dam, Canada. Their data set included the work by Vaid et al. (1985) and Vaid & Thomas (1995) as well as clean sand data from Seed & Harder (1990). The resulting "clean sand" K_σ curve is shown in Figure 1.

2.2 *Stress focus plots of cyclic strength*

Trends in geotechnical data with confining stress are sometimes easier to see when the data are plotted in log-log plots. These log-log plots are termed stress focus plots from Olsen (1994). If data fit as a straight line on a log-log stress focus plot, then these data are well fitted by a simple exponential curve. Stress focus plots were used in this study as a framework for investigating confining stress effects on cyclic strength and CRR.

Stress focus theory (Olsen 1994) shows that curves for cyclic strength, penetration resistance, and other soil properties that are functions of confining stress and density tend to converge as confining stress increases. This point (or zone) of convergence is termed the stress focus, and is a function of soil type and mineralogy (Olsen 1994).

The slope of a line in a cyclic strength stress focus plot corresponds to the inverse of the exponent used by Olsen (1984) to describe K_σ: $K_\sigma=(\sigma'_v)^{f-1}$ (Figure 1). This is shown in the stress focus plot of cyclic strength in Figure 2, which shows generalized stress focus cyclic strength lines for a very loose to dense sand. As density increases, the cyclic strength at a confining stress of 1 atm, CRR_1, increases and the slope, f, decreases. The corresponding K_σ curves ($K_\sigma=(\sigma'_v)^{f-1}$) are shown in Figure 1. As density increases, the exponent f decreases and K_σ decreases, resulting in a more severe reduction to CRR.

2.3 *Observations from the K_σ Database*

The K_σ data were reviewed by soil type (sand, gravel and silt mixtures) and by method of deposition (laboratory pluviation, moist compaction and undisturbed samples of water-laid deposits). The data in Figure 1 are identified by method of deposition. We observed that K_σ is more strongly affected by stress-history, aging effects and density than by soil type. This was most clearly illustrated by the data from Fort Peck Dam. Marcuson & Krinitzsky (1974) report laboratory tests on undisturbed and wet-pluviated reconstructed specimens, as well as in situ blowcounts. The resulting cyclic strengths are plotted in Figure 3.

Figure 4 was used to estimate equivalent $N_{1,60}$ values (based on relative density) for the fine clean sands tested by Vaid et al. (1985) and Vaid & Thomas (1995). In situ $N_{1,60}$ values for the gravel data from WES were estimated from Becker blowcounts. Corresponding values of CRR_1 were estimated from the Seed et al. (1985) liquefaction chart. A comparison of the CRR_1 determined from laboratory tests with values determined from $N_{1,60}$ are shown in Figure 5 as a function of relative density.

Figure 5 indicates that cyclic strengths from laboratory pluviated specimens underestimate CRR_1 values by a factor of about 2 to 3; undisturbed specimens underestimate CRR_1 by about 10 to 20 percent; moist-tamped specimens overestimate CRR_1 at low relative density and underestimate at high relative density.

The pluviated specimens had low cyclic strength and high values of K_σ ($f > 0.9$). However, laboratory strengths from undisturbed specimens and CRR_1 values determined from blowcounts are approximately 2.5 times the strengths from the pluviated specimens. This indicates that the K_σ values from the pluviated specimens are unconservatively high.

3. CONCLUSIONS

We conclude from this study that method of deposition, aging, stress history and density strongly influence K_σ. These effects are emphasized at low confining stresses, such as 1 atm, and are de-emphasized as confining stresses increase, and ultimately converge at the stress focus. Within the stress range of interest for dams, typically less than 10 atm, K_σ is not strongly influenced by soil type. Specimens pluviated in the laboratory may represent recently deposited materials such as dredged and liquefied materials.

However, for water-laid foundation deposits typical for dams, high quality undisturbed specimens are necessary to determine field-relevant values of K_σ.

4. RECOMMENDATIONS

For practical liquefaction evaluations, it is recommended that K_σ be estimated as suggested by Olsen (1984): $K_\sigma=(\sigma'_v)^{f-1}$. For relatively loose deposits the exponent f is about 0.8; f decreases to 0.7 for medium dense, and to 0.6 for dense or slightly overconsolidated deposits. For very dense or higher overconsolidation (stress history and aging effects), the exponent f may be less than 0.6. In their August 1998 meeting, the MCEER International Liquefaction Committee (Youd & Idriss 1997) adopted the K_σ recommendations from this study.

5. ACKNOWLEDGMENT

This study was sponsored by the Civil Works Earthquake Engineering Research Program of the US Army Corps of Engineers, and the Panama Canal Commission. Permission was granted by the Chief of Engineers to publish this information.

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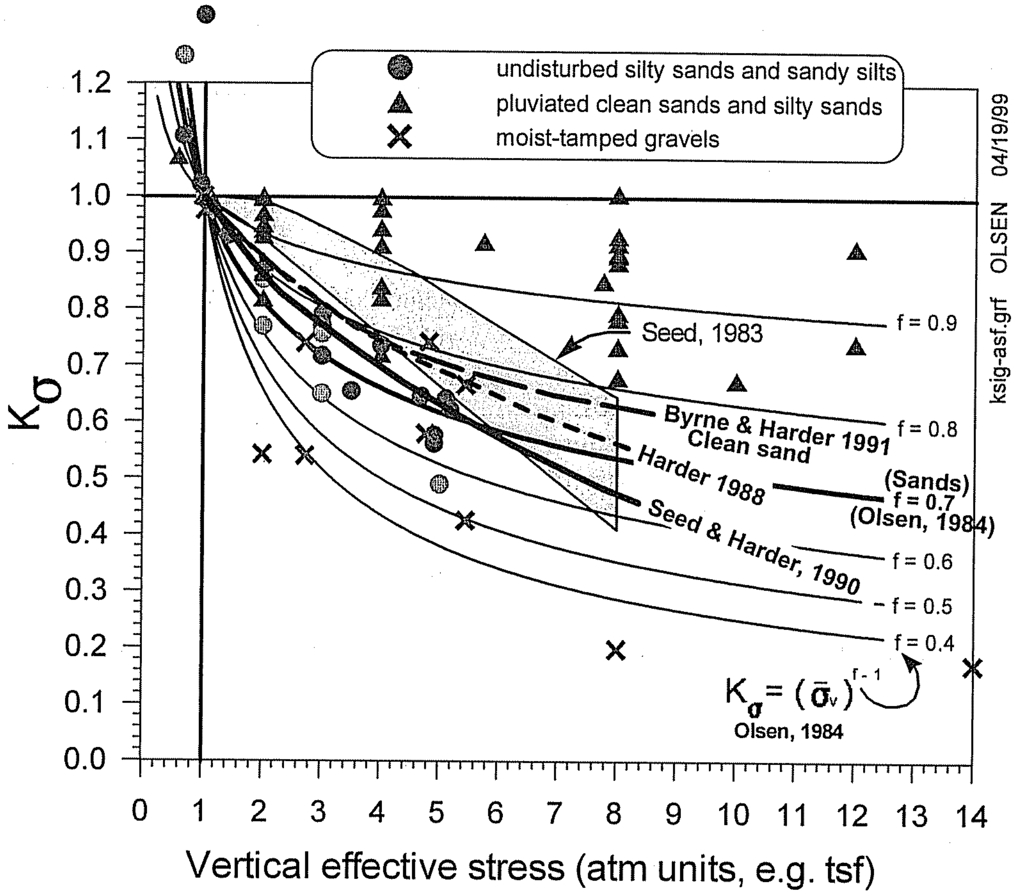

Figure 1 Laboratory data and K_σ relationships

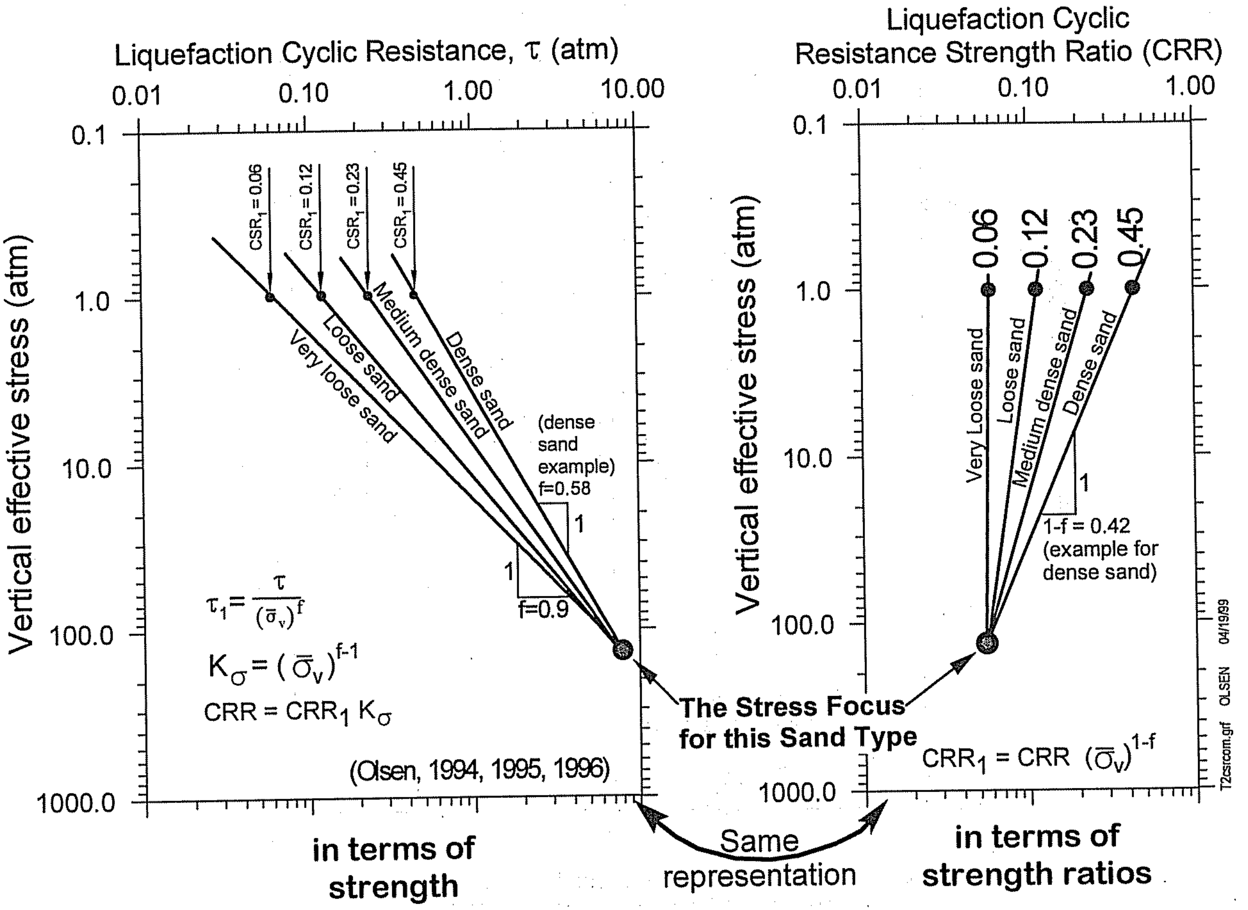

Figure 2 Generalized stress focus plots of cyclic shear strengths and stress ratios

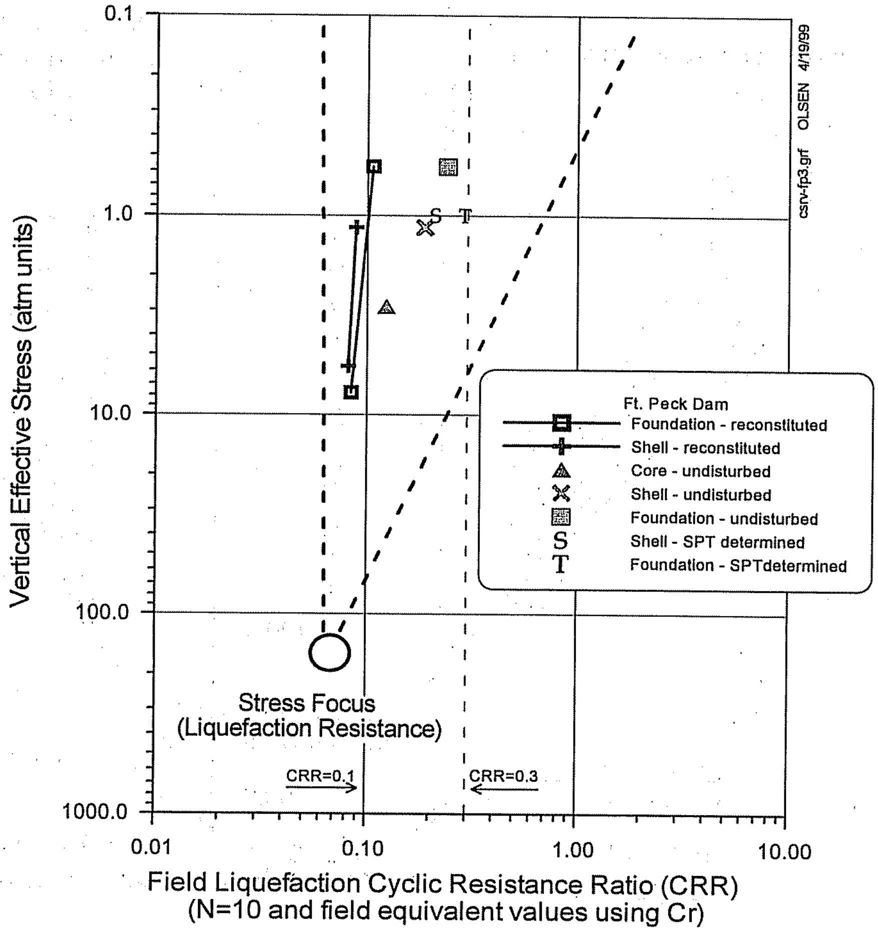

Figure 3 Stress focus plot of field and laboratory estimates of cyclic stress ratios for Fort Peck Dam

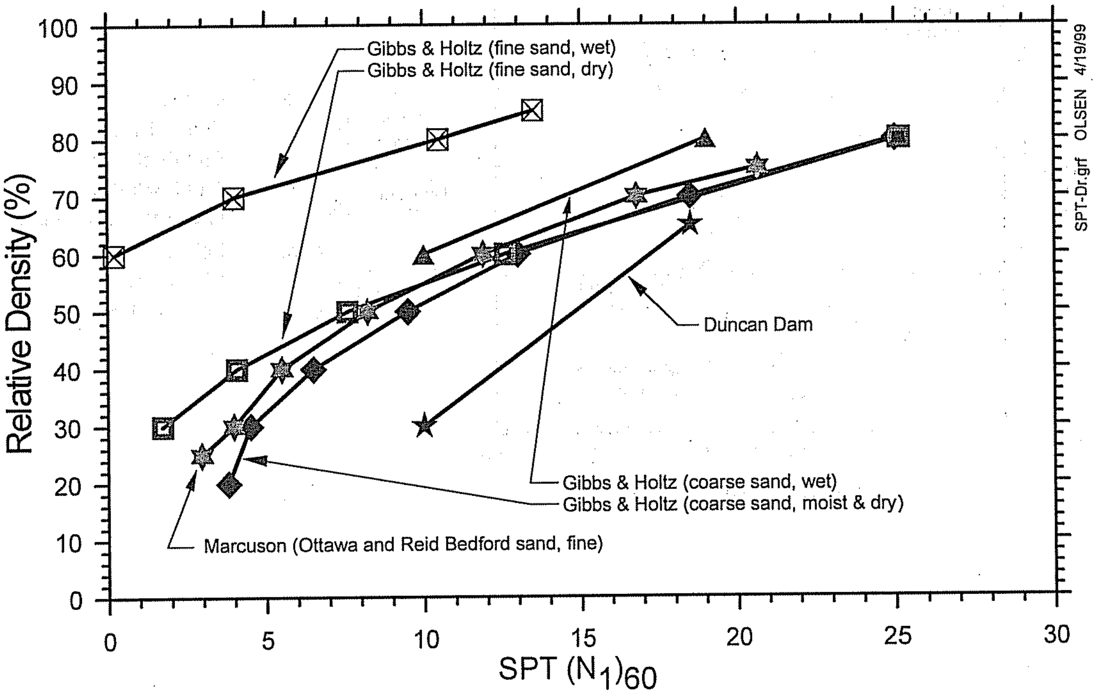

Figure 4 Relationship between relative density and $N_{1,60}$

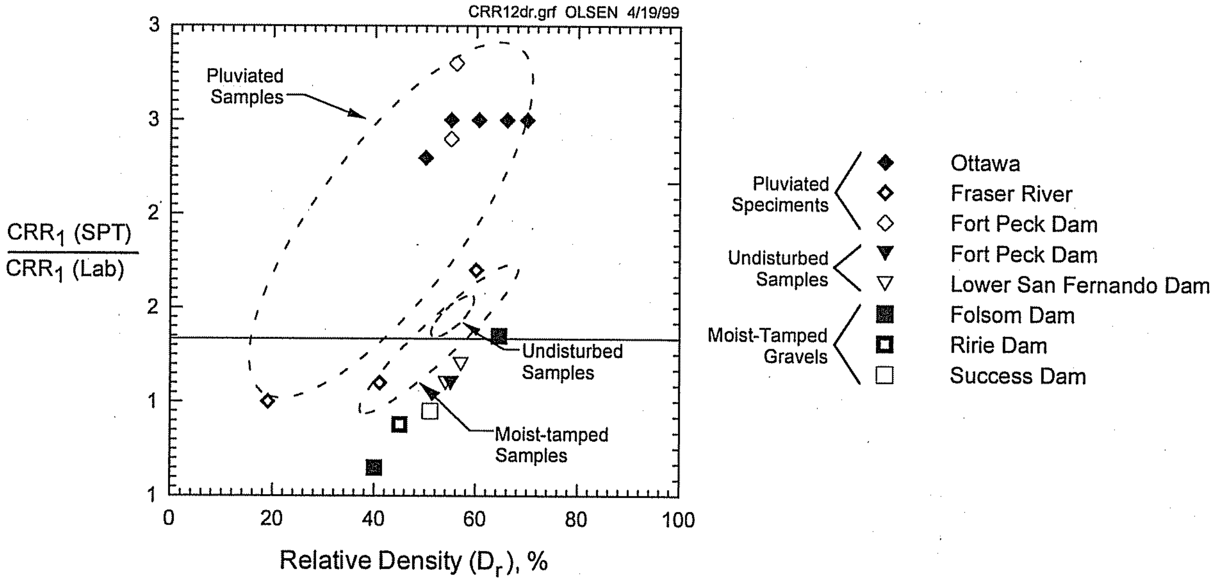

Figure 5 Comparison of CRR_1 from laboratory tests with CRR_1 from SPT blowcounts