Effect of Shaking History on Cone Penetration Resistance and Cyclic Strength of Saturated Sand

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ABSTRACT

The effect of shaking history on cone penetration resistance, cyclic resistance ratio, and their correlation to each other for saturated sand is examined using centrifuge model tests. Prior laboratory and centrifuge modeling studies have shown strain history can have a strong effect on the cyclic strength of sand, but data describing how these effects track with cone penetration resistance are lacking. The effects of shaking history on cone penetration resistance and cyclic strength are investigated using centrifuge models of saturated Ottawa sand on a 1-m radius centrifuge with a 6-mm diameter cone penetrometer. The centrifuge models are subjected to a series of shaking events at progressively increasing amplitudes until liquefaction is triggered. This motion is repeated until the sand no longer liquefies. Cone penetration tests are performed before any shaking, after liquefaction is triggered, and after liquefaction no longer occurs. Inverse analyses of accelerometer array data are used to compute profiles of dynamic shear stresses and strains. The results are used to examine the effects of prior strain history on cone penetration resistance, cyclic resistance ratio, and their correlation to each other. The centrifuge test results are also compared with a case history-based liquefaction triggering correlation.

INTRODUCTION

The Cone Penetration Test (CPT), Standard Penetration Test (SPT), and shear wave velocity \((V_s)\) based liquefaction triggering correlations commonly used in engineering practice have been developed primarily based on case history data. The available case history data do not, however, fully constrain the correlations over the full range of...
conditions of interest to practice. For this reason, it is important that the function terms in the liquefaction triggering analysis framework continue to be guided by a synthesis of experimental, theoretical, and case history based findings.

One source of uncertainty in the development and application of liquefaction triggering correlations has been the potential effects of seismic loading history on the in-situ test measurements, the sand's cyclic resistance ratio (CRR), and the correlation between them. For example, the in-situ test measurements for many of the available liquefaction case histories were obtained after the earthquake. Data from the limited number of case histories with in-situ measurements before and after earthquake loading suggest that the effects of any single earthquake event on the in-situ test measurement are small relative to other sources of uncertainty, and yet it seems apparent that the cumulative effects of multiple events over geologic time should result in a progressive improvement in soil properties.

This paper describes the use of a geotechnical centrifuge to investigate the effects of shaking history on cone penetration tip resistance ($q_c$), cyclic resistance ratio (CRR), and their correlation to each other for saturated Ottawa sand. Details of the model construction, sensor layout, and testing program are described. The analysis procedures for computing cyclic shear stress and shear strain time series from the accelerometer data for each shaking event are outlined. A procedure for determining CRR values from the cyclic stress ratio (CSR) time series up to the time liquefaction is triggered is described. Example results are presented for shaking events in which liquefaction was and was not triggered. Results of cone penetration tests showing a progressive increase in penetration resistance with successive shaking events are summarized. The correlation between cone penetration tip resistance and CRR values over the course of the imposed shaking events is then examined, and compared to the case-history based liquefaction triggering correlation by Boulanger and Idriss (2014). Future directions and the implications for engineering practice are discussed.

**CENTRIFUGE MODEL**

A centrifuge model of a level soil profile comprised of Ottawa sand at a relative density ($D_r$) of 50%, with dimensions as indicated in Figure 1, was constructed in a hinge plate container and saturated with methylcellulose. The model relative density was achieved using the air pluviation method by controlling the drop height and mesh size of the hopper. A hinge plate container was selected for the ability to more freely deform with the soil during shaking, reducing the container influence on the soil’s dynamic response. The hinge plate container uses a latex liner to prevent soil and water loss during testing; comparison of acceleration records from the container and liner base indicate the liner does not significantly influence the model behavior. The model was saturated under vacuum using a methylcellulose fluid mixed to a viscosity 33 times greater than water; the use of a higher viscosity pore fluid improves the simultaneous modeling of diffusion and dynamic processes in the centrifuge. The centrifuge test was performed at a centrifugal acceleration of 80 g. All results are presented in prototype
The model was instrumented with pore pressure transducers (PPTs), accelerometers, and a linear potentiometer (LP) to measure the dynamic response of the soil during shaking. Three PPTs were placed in a vertical array at depths of 1.6 m, 5.5 m, and 8.0 m; an additional PPT was placed at 5.4 m at a different location as a back-up measure. Accelerometers were placed in a vertical array opposite the PPTs at depths of 1.6 m, 5.5 m, 8.0 m, and 9.6 m; additionally, accelerometers were placed on the outside base of the container on the East and West side and inside on the base of the liner to measure the effect of the liner on the soil response. Acceleration data were filtered using a fourth order Butterworth bandpass filter with the corner frequencies of 0.15 Hz and 0.75 Hz to bracket the input sinusoidal motion frequency of 0.5 Hz. A 50 mm stroke LP mounted on an instrument rack provided measurements of ground surface settlements.

The model was subjected to sixteen separate shaking events, each comprised of 15 cycles of sinusoidal acceleration at a frequency of 0.5 Hz. Each shaking event was
separated by about 30 min to allow for a consistent amount of aging and creep between events. In general, the shaking events involved peak base accelerations ranging from 0.018 g to 0.09 g, with each successive event having either an approximately equal or greater peak base acceleration than the prior events.

A 6 mm diameter cone penetrometer was used to measure changes in penetration resistance; profiles were obtained at the locations indicated in Figure 1. Cones were pushed using a hydraulic actuator at a penetration rate of approximately 1 cm/sec. Performing a cone sounding required stopping the centrifuge to mount the cone actuator, spinning the centrifuge up to 80g, performing the cone sounding, and stopping the centrifuge to remove the CPT actuator. This cycle of stopping and spinning can be expected to affect Ko conditions in the model, which would affect both the penetration resistance and cyclic strength of the sand. The potential effects of this cycle of stopping and spinning on the subsequent correlation of cyclic strength with penetration resistance warrants future examination.

CALCULATION OF CYCLIC SHEAR STRESSES AND STRAINS

The correlation of CRR and qc was examined using results obtained at approximately mid-depth in the soil profile because this is where the qc values are free from influence of the ground surface and container base, as discussed in the following section. Shear stress, shear strain, and excess pore pressure ratio (ru) time series at mid-depth in the soil profile were computed from the accelerometer and PPT arrays and used to evaluate the CRR of the sand, as described below.

Shear stress time series were computed using the filtered acceleration data and methods outlined in Kamai and Boulanger (2010). Shear stress was calculated assuming the shear stress was zero at the ground surface and acceleration varied linearly between sensors. CSR time series were computed as the ratio of shear stress to initial vertical effective stress (σ’vo).

Shear strain time series were computed using the weighted residual method outlined in Brandenberg et al. (2010). Displacements were calculated from filtered accelerometer data in the frequency domain and mapped back to the time domain for strain calculations. Strains were calculated at midpoints between sensors and mapped to the PPT depths assuming linear variation between sensors.

The occurrence or nonoccurrence of liquefaction during each shaking event was evaluated based on the excess pore pressure (Δu) and shear strain time series. A peak excess pore pressure ratio, ru = Δu/σ’vo equal to 1.0, which means σ’v has gone to zero, is a common criteria for defining liquefaction under level ground conditions. The triggering of ru = 1.0 in laboratory element tests is typically accompanied by cyclic shear strains reaching values of 1-3%, and thus peak shear strains provided an independent indication of whether liquefaction was triggered or not. These two response measures provided consistent results for all but one shaking event. For the ten events judged to have clearly not triggered liquefaction, the peak values of ru were all
less than 0.8 and the peak shear strains were all less than 0.7%. For the five events judged to have clearly triggered liquefaction, the peak values of $r_u$ were all greater than 0.95 and the peak shear strains were all greater than 1.5%. For shaking Event 11, the soil was judged to have not liquefied based on the peak $r_u$ of 0.78 despite a peak shear strain of 1.6%.

Dynamic responses during shaking events in which liquefaction was not, and was, triggered are shown in Figures 2 and 3, respectively; these figures correspond to events 5 and 6 in the overall test sequence. Event 5 generated small shear strains, low excess pore pressures, and small settlements (Figure 2). Event 6 generated large shear strains, high excess pore pressures, and significant settlements (Figure 3). The shear strains in Event 6 began to rapidly increase at approximately the same time the $r_u$ value near 100%. The surface acceleration in Events 5 and 6 shows negligible amplification or phase lag relative to the base motion prior to liquefaction, which is consistent with the input motion frequency (0.5 Hz) being much smaller than the estimated natural frequency of the soil profile ($\approx$3 Hz). The surface motion begins to show a slight phase lag relative to the base motion after liquefaction is triggered, which is consistent with expected effects of the soil profile's effective natural frequency becoming smaller as the soil's effective stiffness is reduced. The CSRs at mid-depth in the soil profile were largely comprised of 15 stronger, approximately sinusoidal cycles with some variation in amplitudes, followed by some smaller cycles as the dynamic response of the soil model decays.

The non-uniform CSR time series were converted to equivalent uniform CSR time series having 15 uniform cycles ($CSR_{N=15}$) using the weighting procedure introduced by Seed et al. (1975). The weighting procedure utilizes the slope of the relationship between CRR and number of loading cycles on a log-log scale; i.e., the exponent in a power law fit to the cyclic strength data. Results of cyclic undrained direct simple shear (DSS) tests conducted on Ottawa sand samples with similar relative densities and over-burden stress are shown in Figure 4; The power law fits to these data indicate the slope is approximately 0.15. Loading cycles with a CSR amplitude less than 10% of the peak CSR were not included; this corresponds to the small decaying motions after the end of strong shaking, and including them or not has a negligible effect on the computed equivalent uniform CSR.

The CRR of the soil is, by definition, the CSR loading required to trigger liquefaction. The CRR was thus determined using the CSR time series up to the time at which liquefaction was triggered. The CRR was similarly converted to 15 uniform loading cycles ($CRR_{N=15}$), which means the $CRR_{N=15}$ will be smaller than the $CSR_{N=15}$ for the full CSR loading history by an amount which depends on the time at which liquefaction was triggered. For example, the full CSR time series at mid-depth in Event 6 (Figure 3) corresponds to a $CSR_{N=15} = 0.109$ whereas the $CRR_{N=15} = 0.106$ because liquefaction was triggered about 5 seconds before the end of strong shaking.
Figure 2. Dynamic response for Event 5, which did not trigger liquefaction.
Figure 3. Dynamic response for Event 6, which did trigger liquefaction.
CONE PENETRATION RESISTANCES

Measured cone penetration resistance profiles were obtained prior to Event 1, after Event 6 (the first event triggering liquefaction), and after Event 13 (the first event to not trigger liquefaction with a CSR \( N=15 \) of approximately 0.115); penetration resistance profiles for all three times are shown in Figure 5. The measured cone penetration resistance was increased by the shaking history. The amount of increase is greater between Events 7 and 13 (which spans several events triggering liquefaction) compared to the increase between Events 1 and 6 (which spans only one event triggering liquefaction), suggesting that the liquefaction events induced greater changes in penetration resistance compared to non-liquefaction events.

Penetration resistances were normalized to an equivalent \( \sigma'_v = 50 \) kPa, which is approximately the effective vertical stress at mid-depth in the soil profile. This normalization was performed using the overburden correction factor, \( C_N \), described in Boulanger and Idriss (2014) modified to a reference stress of 50 kPa (i.e., 0.5 atm). A reference stress of 50 kPa was chosen so results could be presented with the least amount of correction applied to measured values. Penetration resistances were further normalized by atmospheric pressure (\( P_a \)) to arrive at the dimensionless, normalized penetration resistance, \( q_{c0.5N} = q_{c0.5}/P_a \).

A representative penetration resistance for use in correlations was selected by averaging penetration resistances over the depth interval 2.5 cone diameters above and below the depth of the mid-depth PPT (4.3 m to 6.7 m). The mid-depth PPT was selected for analysis since this sensor is located the greatest distance from interfaces (the surface and base). The average \( q_{c0.5N} \) for CPTs 1-3 are 25.3, 34.4, and 64.5, respectively.

Figure 4. Undrained cyclic DSS tests on loose, saturated, Ottawa sand.
Values of $q_{c0.5N}$ at the start of other shaking events were estimated based on the measured settlement from prior events. The normalized penetration resistance was assumed to vary linearly with settlement between the CPT tests. This linear interpolation, anchored by the three CPT tests, results in a bi-linear relationship between settlement and $q_{c0.5N}$. Values for $q_{c0.5N}$ for the four events after CPT 3 are assumed to follow the same relationship as between CPTs 2 and 3, which is considered reasonable given the similar values of imposed CSR.

**CORRELATIONS**

The results of the centrifuge test are presented Figure 6 in terms of applied $CSR_{N=15}$ and interpreted $CRR_{N=15}$ values versus $q_{c0.5N}$ values. Solid bullet points correspond to events in which liquefaction was triggered, and open bullet points correspond to events for which liquefaction was not triggered; these points are plotted at the $CSR_{N=15}$ values for the full time series. Solid diamond points correspond to the $CRR_{N=15}$ values obtained from the events in which liquefaction was triggered. The correlation of $CRR_{N=15}$ to $q_{c0.5N}$ would thus be expected to intersect the diamond points, whereas open
The CRR\textsubscript{N=15} values from the centrifuge data (Figure 6) are in reasonable agreement with the DSS results (Figure 4), allowing for their slight differences in initial relative densities. The centrifuge test with its initial D\textsubscript{R} of 50\% indicates a CRR\textsubscript{N=15} of around 0.10, whereas the DSS tests with their initial D\textsubscript{R} of 40\% indicate a CRR\textsubscript{N=15} of about 0.085. This agreement provides support for the procedures used to determine a CRR\textsubscript{N=15} from the recorded responses in the centrifuge tests.

The centrifuge results are also compared in Figure 6 to the case history-based liquefaction triggering correlation by Boulanger and Idriss (2014) mapped to the reference \(\sigma'_v = 50\) kPa. The Boulanger and Idriss (2014) correlation is shown for an earthquake magnitude \(M = 7.5\) (for which the CRR values are considered as being represented by an equivalent 15 uniform loading cycles) and a probability of liquefaction (P\textsubscript{L}) of 15\%, 50\%, and 85\% based on model uncertainty alone. The centrifuge data generally agrees with the case history CPT correlations, with the data falling near and along the P\textsubscript{L} = 15\% curve. These results further suggest that the correlation of CRR with cone penetration resistance in clean sand is not significantly dependent on shaking history, at least for the range of conditions examined in this test.

The reasonable agreement between these centrifuge test results and the case history based triggering correlation shown in Figure 6 is encouraging given the differences
between model and field conditions. The model tested is a young, freshly deposited soil with an age measured in hours, for which the CRR may be expected to be smaller compared to geologically aged sand deposits with similar penetration resistances. This effect may, however, be partially offset by the fact the model was subjected to one-directional horizontal shaking, for which the CRR may be expected to be about 10-15% greater than for the bi-directional horizontal shaking implicitly included in case history based correlations. Despite these and other differences between the model and field conditions, the good agreement between these centrifuge test results and the case history based correlation shown in Figure 6 provides encouragement for the continued use of centrifuge model testing to help guide further advances in CPT based liquefaction triggering correlations.

CONCLUSIONS

A centrifuge test was performed to study the effect of shaking history on cone penetration resistance, cyclic resistance ratio, and their correlation to each other for saturated Ottawa sand. An instrumented model of a level soil profile was spun at 80g and subjected to a series of shaking events, each comprised of 15 cycles of 0.5-Hz sine waves with acceleration amplitudes ranging from 0.018g to 0.09 g. Accelerometer array data was used to calculate cyclic stress ratio time series for each event, from which equivalent uniform cyclic stress ratios and cyclic resistance ratios were determined. Cone penetration tests were used to track the evolution of penetration resistance over a sequence of shaking events, including events which did, and did not, trigger liquefaction.

The centrifuge test results are in reasonable agreement with the case history-based liquefaction triggering correlation by Boulanger and Idriss (2014), with the centrifuge data generally falling near and along their P_L = 15% curve. These initial results also suggest that the correlation of cyclic resistance ratio with cone penetration resistance in clean sand is not significantly dependent on shaking history, at least for the range of conditions examined in this test. Additional centrifuge tests are needed, however, to examine the effect of shaking history over a broader range of initial relative densities, ground motion sequences, soil types, and other variables.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-1300518. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors appreciate the above support and the assistance of the staff in the Center for Geotechnical Modeling.
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