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Evaluating liquefaction risk for varved soils in the Northeastern US

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ABSTRACT

Varved soils were formed by glacial lakes and are predominantly composed of inter-layered clay (CL) and silt (ML, or CL-ML) laminations interspersed with occasional sand (SM) laminations. Liquefaction susceptibility for these varved soils has not yet been well-studied and presents unique challenges. Applying simple liquefaction screening criteria to varved soils from several regional projects show that soils from different laminations within the same sample suggest very different degrees of liquefaction susceptibility. As such, these screening tools do not provide clear guidance on the likely response of varved deposits as a whole. To obtain site specific data, Cyclic Simple Shear (CSS) tests were performed at the UC Berkeley Geotechnical Laboratory on specimens from “undisturbed” tube samples from several sites. The specimens were subjected to undrained loading equivalent to CSRs from site response analyses. The testing showed that for the regional tectonic setting these varved soils have sufficient strength to resist liquefaction likely due to moderate shaking level and their overconsolidated nature. However, under higher strains and multiple cycles these soils could sustain severe loss of strength.

Varved Regional Soils

Varved glacial lake sediments (“Varved soils”) are unique to the Northeast United States (US). They are comprised of finely laminated varves of silty fine sand, silt, and clay (Fig. 1), formed during the Pleistocene epoch. They are predominantly composed of inter-layered clay (CL) and silt (ML or CL-ML) laminations interspersed with occasional sand (SM) laminations. A series of glacial advances across the region scoured deep valleys into the bedrock and older soils, which then filled with dense glacial till and loose outwash sand. Where terminal moraines created dams across the valley, varved silt and clay was deposited in the resulting glacial lakes (Fig. 2).



Figure 1. Varved soil sample (scale: several cm or tenths of feet). After Nikolaou et al., 2012.

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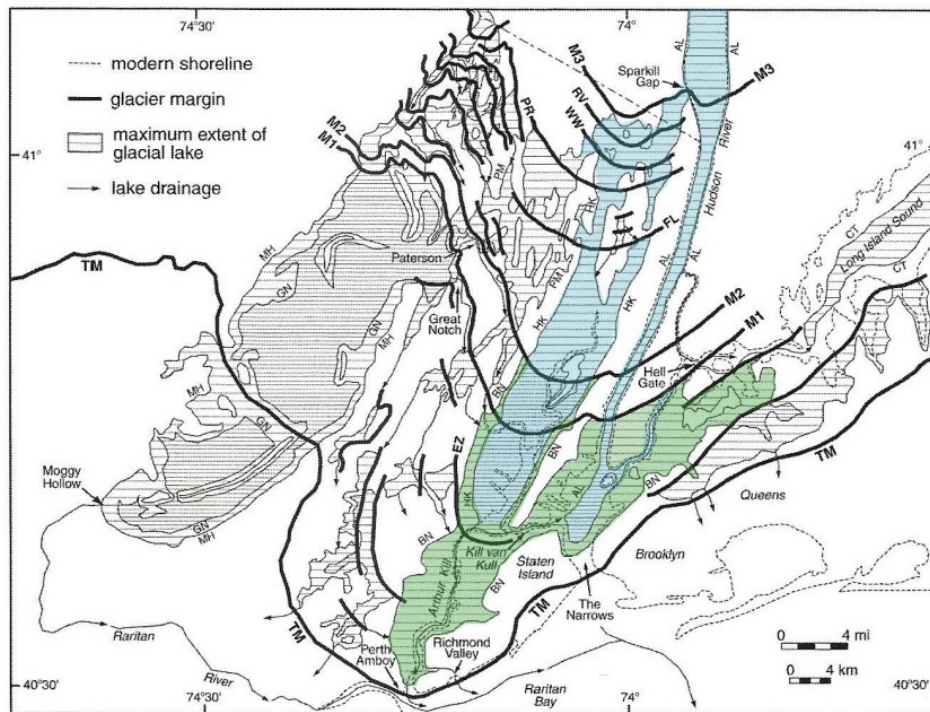


Figure 2. Glacial lakes and ice margin during late Wisconsin retreat (Stanford, 2010): AL-Albany, BN-Bayonne, CT-Connecticut, HK-Hackensack, PM-Paramus, MH-Passaic, GN-Passaic.

Each set of varves represents a seasonal cycle of warm and cold periods, creating the varved or layered texture: silty and sandy materials were deposited on the lake bed during active, warmer periods, while finer clayey materials were deposited during calmer, colder periods. Examples are remnants of glacial Lake Flushing in New York City (NYC), locally known as “bull’s liver” because of their instability when excavated below the ground water (Moss & Merguerian, 2005; Tamaro et al., 2000).

In 1976 J. Parsons of Mueser Rutledge Consulting Engineers (MRCE) described the engineering characteristics of the varved silts and clays found in the NYC area. As documented in the numerous case studies in Parsons (1976), the varved soils of New York were highly overconsolidated. This densification was attributed to a possible younger glacial advance. There is a divergence of opinion among geologists as to the number and timing of ice sheets in this area. In the city there is evidence of an Illinoian age glaciation, two Wisconsin age advances, and at least one minor readvance over portions of the city as the last glacier started its retreat. Each of these advances loaded and consolidated the sediments below.

In NYC, north of the Harbor Hill terminal moraine the soil profile typically consists of bedrock often overlain by a layer of basal till. Above the till, the soil tends to be more coarse-grained towards the present ground surface and more fine grained with depth. Varved silts and clays are often just above the basal till. The deposits coarsen upward into varved silts, then silty fine sands, and eventually into clean fine to coarse grained outwash sands. Locally, there may be

areas with discontinuous, often thin till above the outwash, quite possibly the result of the post-Harbor Hill Woodfordian glaciation (Moss & Merguerian, 2010). In the river valleys the glacial deposits are typically overlain by river sands and organic silty clays and in upper Manhattan varved silt deposits tend to be especially thick compared to the rest of the island (Figs 3, 4).

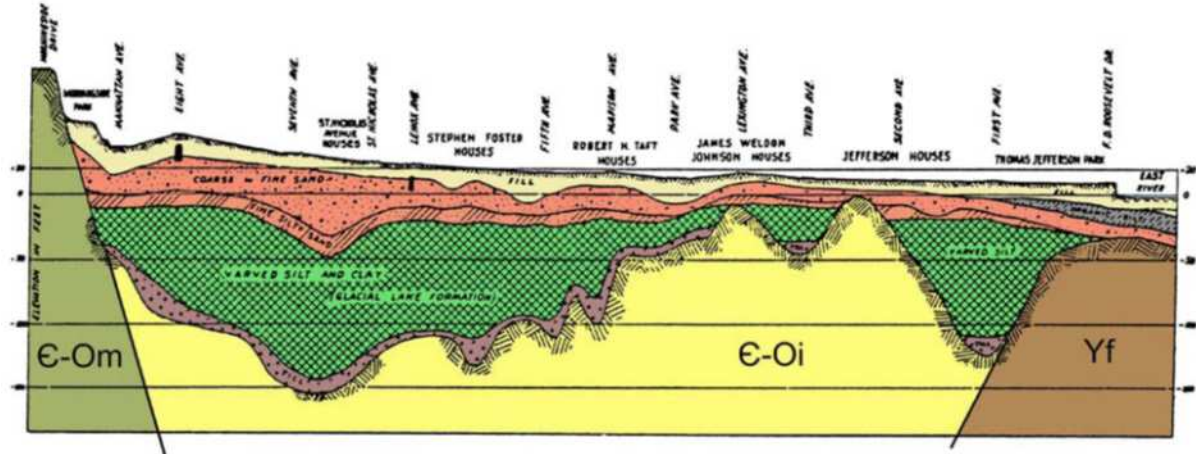


Figure 3. Geological section across 113th Street in Manhattan (see Fig. 4). Units C-Om = Manhattan Schist, C-Oi = Inwood Marble, Yf = Fordham Gneiss. (modified from Parsons, 1976)

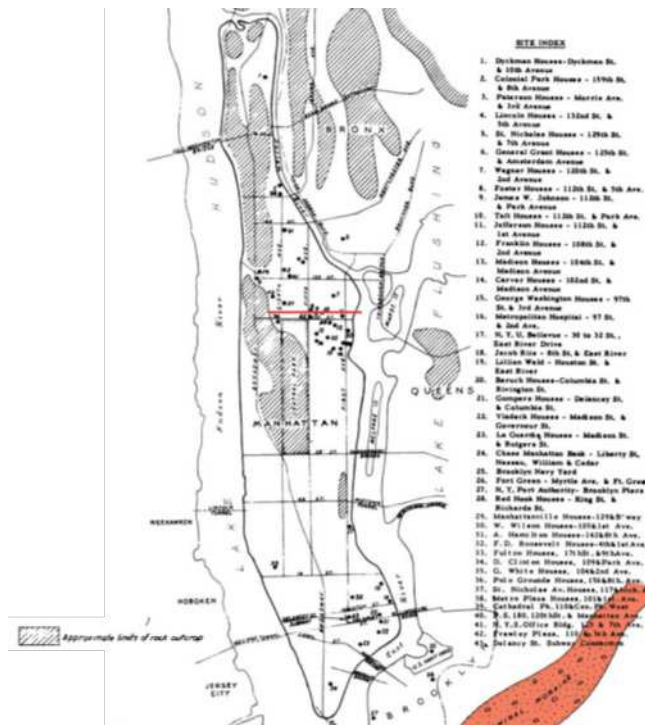


Figure 4. Varved soil sites in Parsons (1976). The red line across 113th St. is the section in Fig. 3.

Varved soils have been used to support structures in Northeast US. Typical foundations include shallow foundations (mat or spread footings) bearing on outwash sands that overlie the varved (D'Argenzio et al., 2004) or deep foundations bearing within the varved such as tapered closed

end pile, or augercast piles (Canale et al., 2009). NYC project examples are shown on Fig. 5: Newtown Creek Water Pollution Control Upgrade (mat foundation) and Citifield Stadium (piles).

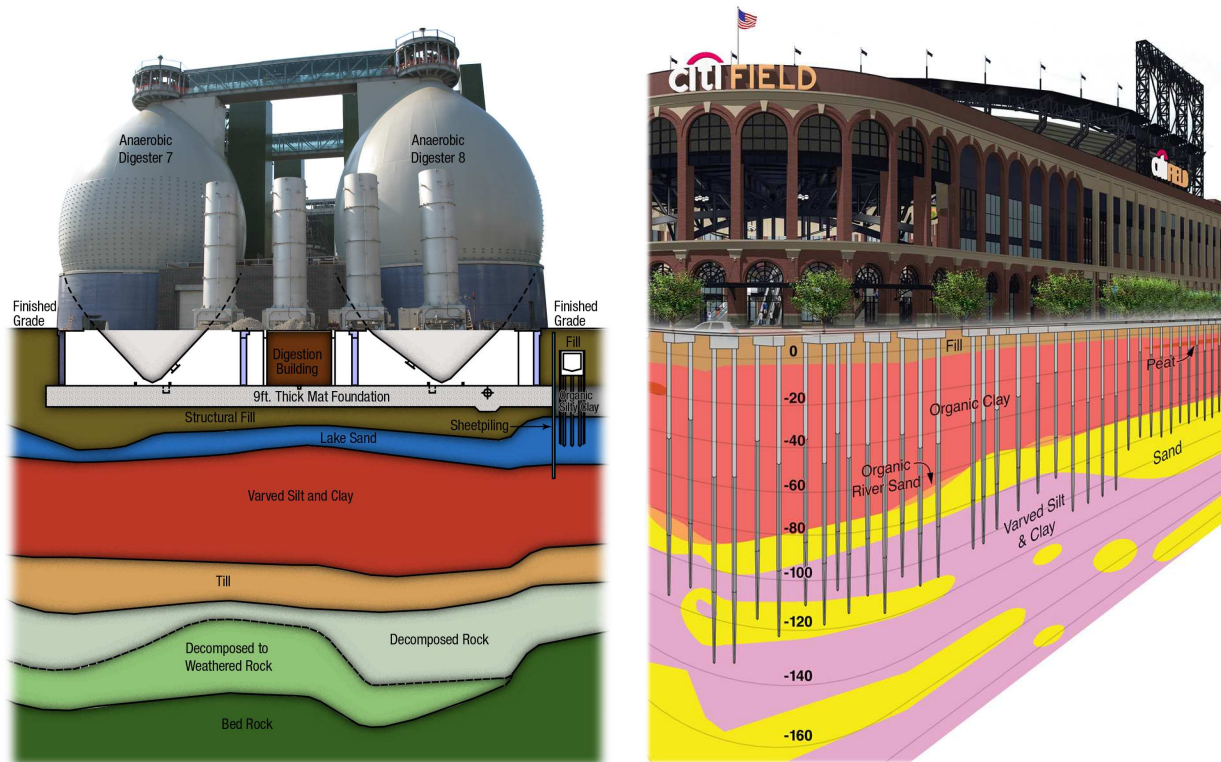


Figure 5. Foundation within varved soils: mat at Newtown Creek Water Pollution Control Upgrade (left, D’Argenzio et al., 2004) and pile foundations at Citifield Stadium (right, Canale et al., 2009).

Liquefaction Potential

Although the varved silt is compressible, it’s is generally overconsolidated and recompression settlements from building loads can be accounted for in the design of the structure. Therefore, understanding the liquefaction potential of these soils is important for current structures and futures structures that will derive support from these soils.

While procedures for assessing liquefaction potential for uniform cohesionless soil deposits are readily available, the same is not as straightforward for some regional fine-grained soils, such as the unique to the Northeastern US varved glacial lake sediments. The varves, or layers of distinctly different soils are often quite thin, even when the overall deposit may be many meters in thickness, and thereby requires consideration of the liquefaction behavior of layered systems.

This raises questions about whether the different materials should be evaluated separately for their liquefaction potential, or what sorts of field or laboratory methods might be effective in evaluating the likely response of the overall deposit. For example, a Cone Penetration Test (CPT) senses the response of a zone of soil around the penetrometer tip, and therefore is providing information about the “average” material response – but care must then be used in

estimating how the measurements may relate to field response if the correlations are based on uniform soils. In contrast, if soils from individual layers are carefully separated and index properties are measured separately, screening criteria can be applied to each distinct material.

Recent case histories indicate that non-plastic and low plasticity silts could liquefy, while plastic silts and clays may experience cyclic softening when subjected to sufficient seismic loading. Bray & Sancio (2006) proposed a criterion to estimate susceptibility to liquefaction using laboratory tests for Plasticity Index (PI), moisture content (w_c), and Liquid Limit (LL). Liquefaction susceptibility for varved soils has not yet been well-studied and presents unique challenges.

In Fig. 6 we have applied the Bray & Sancio (2006) criterion on varved soil samples from three regional projects. Data plotting as “Not Susceptible” are from higher PI clay-like laminations, while points plotting as “Susceptible” or “Moderately Susceptible” are from silt laminations. While this screening identifies types of soil (based on PI) that may be liquefiable in their current state (as per the liquidity index w_c/LL), it does not incorporate the seismic environment, and does not predict whether a given deposit is “likely” to liquefy in the design earthquake. In varved soils, the laminations of sands and non-plastic silts may appear to be susceptible to liquefaction, while the more plastic silts and clays may not be susceptible, or may experience cyclic softening. It is not clear for finely layered systems what the overall susceptibility of the larger scale deposit is.

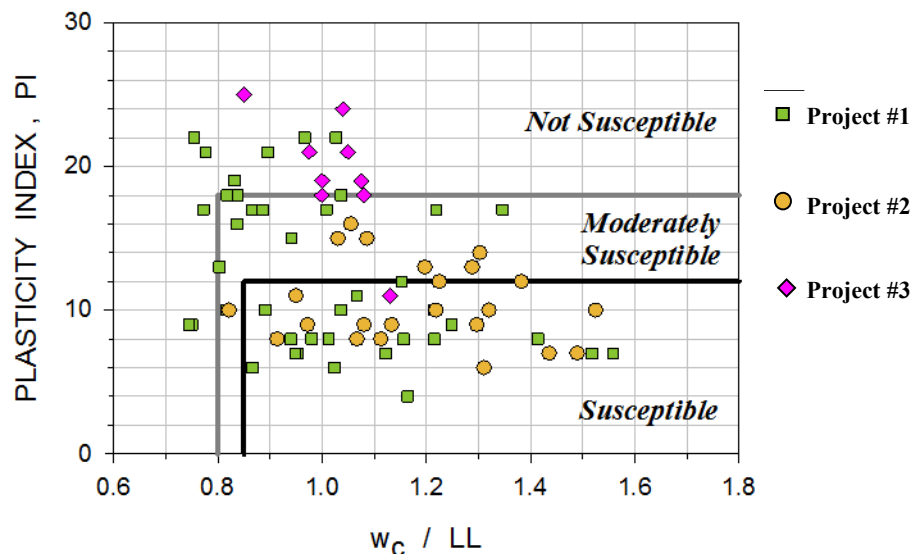


Figure 6. Susceptibility of varved samples from 3 regional projects using Bray & Sancio (2006).

Laboratory Testing

Samples from one of the projects of Fig. 6 were carefully packed and transported to UC Berkeley’s Geotechnical Laboratory for Cyclic Simple Shear (CSS) tests to investigate their potential response to seismic loading. In CSS testing, specimens from “undisturbed” tube samples were carefully extruded, trimmed, saturated and reconsolidated to estimated field stress conditions prior to subjecting them to undrained cyclic loading. During trimming (Fig. 7), the

laminations of coarser and finer grained materials were thin enough to include multiple distinct layers within the approximately 2 cm thick specimens. Wire-reinforced membranes were used to maintain K_0 strain conditions, and specimens were back-pressure saturated prior to consolidation and testing. Cyclic loading was conducted using sinusoidal, stress-controlled horizontal shear stresses of constant peak amplitude, as characterized by the Cyclic Stress Ratio (CSR). The loading frequency was 1 Hz in order to maintain reasonable field loading rates, although the fine-grained nature of the soil precluded making representative measurements of pore pressure or effective stress at this rate.

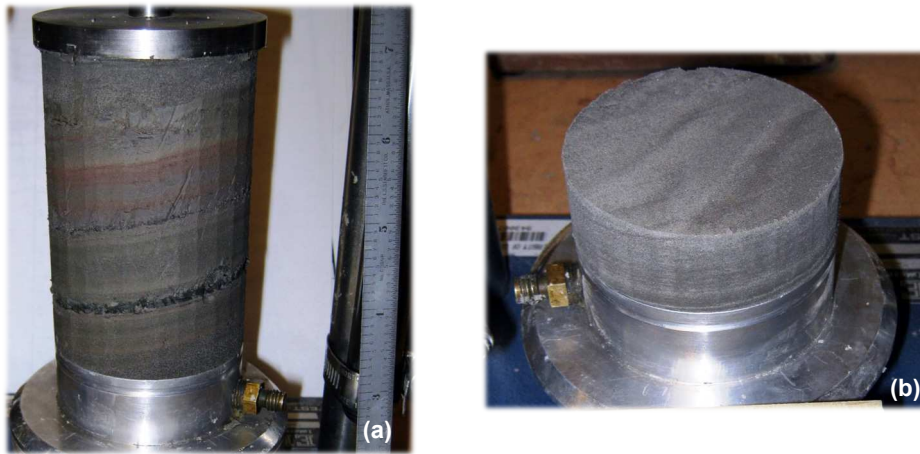


Figure 7. Trimming varved soil sample to: (a) correct diameter and (b) final height. Note thin varving with many alternating layers even within the 18 mm tall CSS specimen.

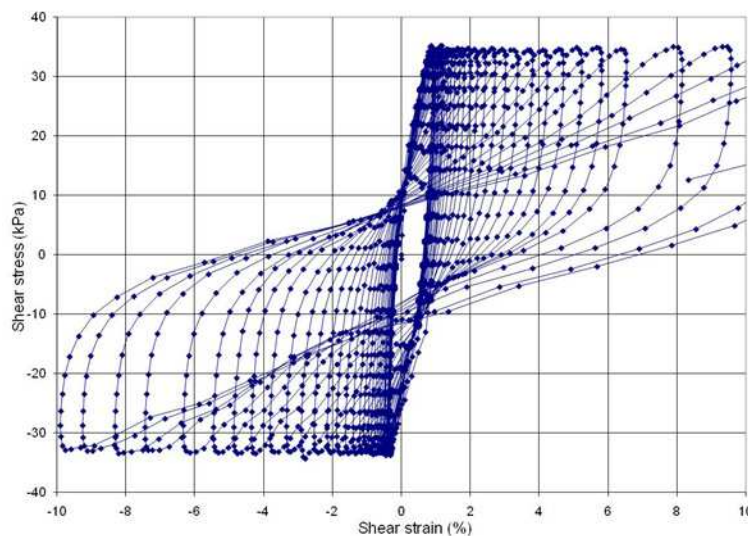


Figure 8. Hysteretic stress-strain response of interlayered silt specimen at a CSR = 0.29, showing cyclic softening at large strains in undrained loading.

Figure 8 shows cyclic stress-strain response of an inter-layered, predominantly silt specimen with overall PI of about 3 tested under undrained conditions following consolidation to a vertical

effective stress of 116 kPa. It clearly shows the degradation of stiffness and softening of the hysteretic response that is typical of contractive soils in undrained cyclic loading. Significantly, however, the loops remain relatively thick even when the peak-to-peak shear strain reaches 20% and beyond – unlike classic liquefaction of cohesionless material in which the shear stresses remain close to zero over a substantial strain range.

Seismic Demand

The ground motions in the Eastern US have unique characteristics, mainly due to the very a hard bedrock and the regional overburden soils. These characteristics affect geoseismic analyses due to high impedance contrast between rock and soil, and the vibrational differences between the predicted high-frequency bedrock motions and low-frequency deep soft sites. Due to lack of Eastern US strong motion records, regional practice typically modifies earthquake motions recorded in more seismically active areas such as California to match the predicted (from Probabilistic Seismic Hazards Analysis) bedrock motions. To illustrate the differences in the frequency content of Western vs. Northeastern US, Fig. 9 shows examples of 3 pairs (in two orthogonal directions) of original seed and spectrally-matched rock time histories to a uniform hazard at the site where samples of Fig. 7 were taken, with return period T_r of 2,500 years.

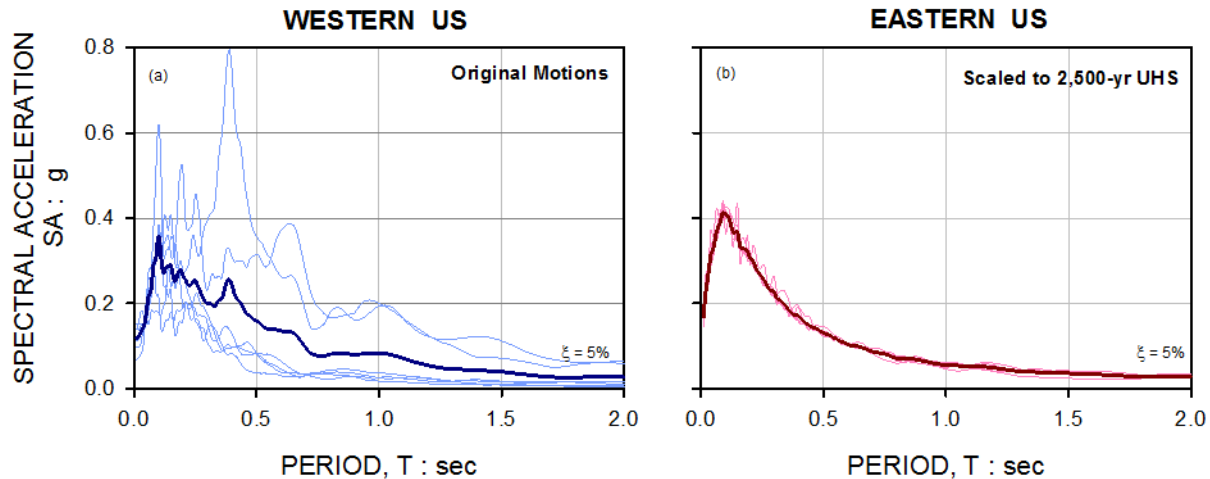


Figure 9. Original Western (a) and scaled Eastern US (b) rock spectra for uniform hazard with T_r of 2,500 years at the site where the soil samples of Fig. 6 were taken (after Nikolaou et al., 2012).

Based several site-specific liquefaction assessments in the region, the seismic demand (or Cyclic Stress Ratio, CSR) calculated based on stresses in the soil are significantly smaller than the ones calculated based on the simplified procedures based on the r_d factor that appears to decrease significantly faster with the site-specific results. This may be attributed to a form of incoherency or non-resonance of the subsurface soils to the input rock ground motions that have much shorter predominant period (~ 0.04 sec). Although frequency characteristics of ground motions have been inherently incorporated in Idriss & Boulanger (2008) and Cetin et al. (2004), further developments are needed to better capture Northeast US site response (Nikolaou et al., 2012). Figure 10 summarizes the number of cycles required to initiate liquefaction (defined as 5%

single-amplitude shear strain) as a function of the applied CSR for five specimens of varying gradation subjected to Cyclic Simple Shear (CSS). To take a conservative approach, less cohesive (and therefore more liquefiable) specimens were selected for testing (Fig. 7). In this regional Northeast US case study, it appears that the varved soils have sufficient strength to resist liquefaction likely due to the moderate shaking level with CSR on the order of 0.15, and their overconsolidated nature.

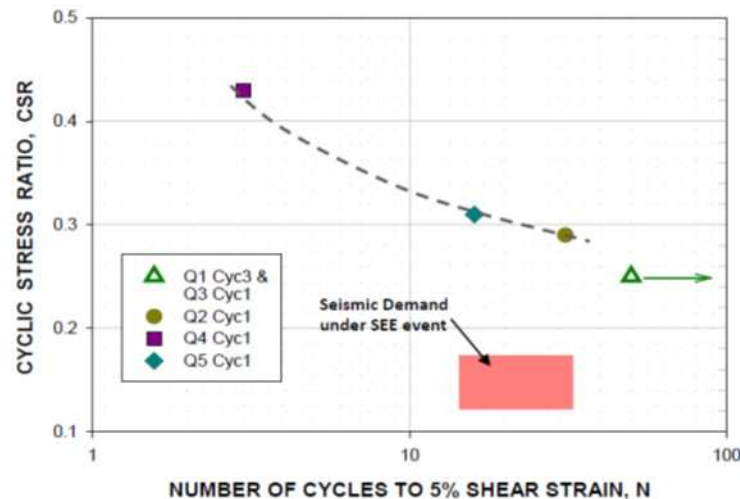


Figure 10. Cyclic Simple Shear (CSS) test results on varved soil samples.

Conclusions

Varved glacial lake sediments are unique to Northeast US. Current liquefaction evaluation procedures need to be regionally adjusted to take into account incoherency resulting from the high frequency ground motions and relatively low natural period of the overburden soils. Cyclic simple shear tests performed in varved samples conducted at the laboratory of UC Berkeley showed that these samples had sufficient strength to resist liquefaction likely due to the moderate expected shaking level with CSR demand of about 0.15 and their overconsolidated nature. Liquefaction susceptibility of the regional fine-grained varved silts and clays needs to be further studied.

Acknowledgments

The authors gratefully acknowledge MRCE colleagues that contributed with previous publications and project data, and the Partners of the firm who supported the manuscript preparation.

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