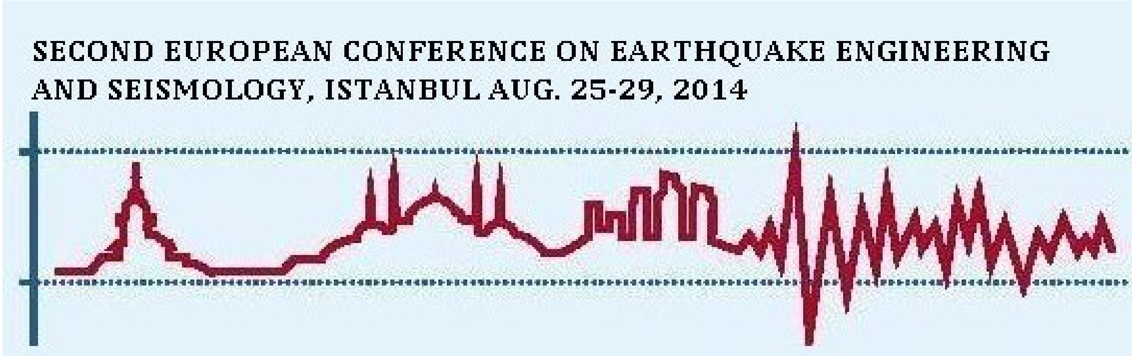

THE LIQUEFACTION POTENTIAL OF A MARINE SILT LAYER – A CASE STUDY FROM CHÂTEAUGUAY, QUÉBEC, CANADA

Nick SARTAIN[1], Denis LEBOEUF[2], Romeo CIUBOTARIU[3], David GARCIA-CUETO[4] and Ziggy LUBKOWSKI[5]

ABSTRACT

A site in Châteauguay, south of Montréal, Québec, Canada, was investigated as part of the design of a significant infrastructure project. A loose marine silt layer present at the site was found to be susceptible to liquefaction using conventional empirical techniques based on CPT, SPT and classification data.

To mitigate this hazard, a program of careful undisturbed sampling and advanced laboratory testing, including cyclic direct simple shear testing, was undertaken to investigate in detail the properties and cyclic behaviour of the soil. The magnitude of cyclic loading was determined from the site-specific seismic hazard assessment and site response analyses. Post-cyclic testing of the static strength of the soils was undertaken to establish the residual strength of the soils.

The laboratory results confirmed that the silts would soften under this cyclic loading but that they would not liquefy. The use of conventional liquefaction assessment techniques was found to be conservative in these soils.

INTRODUCTION

The Nouvelle Autoroute 30 (NA30) project is located south of the island of Montréal, between Vaudreuil-Dorion and Châteauguay in Québec, Canada, as shown in Figure 1. Montréal is in an area of moderate seismicity, and it is a local requirement that seismic analysis of new highway earthworks be performed.

At the east end of the project, in Châteauguay, it was necessary to construct a cutting approximately 6m deep and 1km long. Locally the soils were found to include a thin deposit of loose silts, when clays were typical elsewhwere. It was necessary to review these soils for their potential for liquefaction as part of the design since the consequences of failure of the cutting slopes were potentially significant. Conventional techniques for assessing liquefaction potential were used based on classification (Bray and Sanchio, 2006), SPT and CPT data (Youd et al. 2001) and all indicated liquefaction was likely. This paper presents the findings of the subsequent programme of field and laboratory work that was undertaken to mitigate this risk by demonstrating that the silt deposits had higher liquefaction resistance than is predicted by these conventional techniques.

[1] Associate, Arup, Solihull, nick.sartain@arup.com
[2] Professor, Laval University, Quebec, Denis.LeBoeuf@gci.ulaval.ca
[3] Director, Geotechnical Group, Aecom, Montréal, romeo.ciubotariu@aecom.com
[4] Engineer, Acciona, Sydney, david.garcia.cueto@acciona.com
[5] Associate Director, Arup, London, ziggy.lubkowski@arup.com

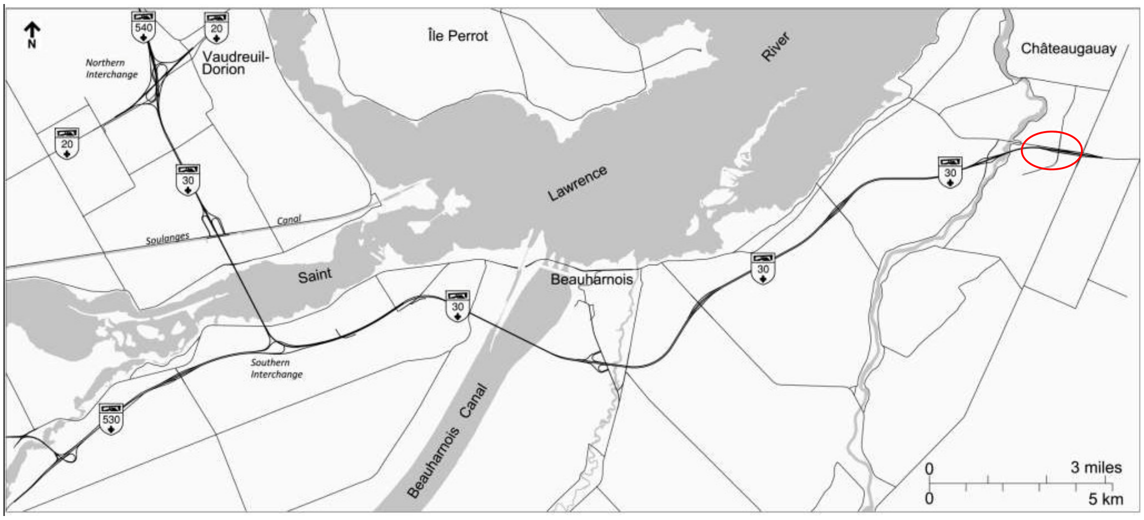

Figure 1. Nouvelle Autoroute 30 route alignment, with the Châteauguay Cutting at the easternmost end.

GEOLOGY AND GROUND CONDITIONS

The town of Châteauguay is located on the south shore of the St Lawrence Lake, opposite the island of Montréal. Châteauguay and its surroundings are found on a relatively flat plateau with ground level typically around 38m above sea level.

The drift deposits comprise the post-glacial Champlain Sea Deposits and the glacial deposits from the former Wisconsian Glacier. The Champlain Sea Basin is one of the major Quaternary basins in Canada and the geology of the marine clay and underlying deposits of eastern Canada is well documented in the literature (Gadd, 1988 and Quigley, 1980). The offshore marine deposits from the Champlain Sea comprise mainly 'rock flour' material of a clay and silt size. The material structure was formerly held together by the sea water ions, but with the replacing of the sea water with fresh water the material exhibits 'sensitive' properties. The material structure is vulnerable to disturbance and collapse, with the rock flour clays and silts readily losing structure and strength. This is assisted by the large volume of water present within the rock flour porosity, typically at or above the liquid limit of the material.

The ground conditions at Châteauguay comprise soft, sensitive Champlain Sea Deposits up to 14m thick, overlying granular coarse (gravelly, with boulders) Glacial Till of typically 2m thickness, which in turn overlie a quartzite and dolomitic sandstone bedrock. The upper 1m to 3m of the Champlain Sea Deposits consists of a stiffer, weathered brown clay "crust" that overlies softer and more brittle unweathered grey clay. With increasing depth, the Champlain Sea Deposits become coarser, until they are a clayey silt, with occasional sand lenses. The clayey silt layers can be up to 4m in thickness.

The water table was typically 5m below ground level.

GROUND INVESTIGATION DATA

During the design period a number of phases of ground investigation were undertaken. Initial phases were relatively sparse but provided the basic information required for preliminary design. Additional data was acquired through detailed design as the design team tried to understand the ground conditions in more detail to minimize the ground-related risks at the cutting location, and specifically the potential for the coarser Champlain Sea Deposits to liquefy.

Boreholes were used to provide a detailed description of the ground, to provide Shelby tube samples for conventional laboratory testing (classification, strength, 1-D stiffness), SPT data and to measure the groundwater pressures. These were complemented by a number of CPT and seismic-CPT holes.

The ground conditions were found to be complex, particularly towards the base of the Champlain Sea Deposits, where the silt and clay fractions are interlayered. There were no clear stratigraphic boundaries, but the Champlain Sea Deposits consistently included the silt stratum and the presence of a continuous layer of this material was considered likely.

The Champlain Sea Clay at the site has typical properties for this material. It is a silty clay of high to very high plasticity (plasticity index >35%, and often >45%, liquid limit >60%). Its natural moisture content is high, with liquidity index on tested samples between 0.4 and 1.0. The shear strength of the clay is variable, and was measured between 13kPa and 66kPa by in-situ Nilcon vane testing, and between 19kPa and 33kPa in unconsolidated undrained triaxial tests. The measured sensitivity was between 4 and 12.

With increasing depth, the silt content increases, and the plasticity falls. The silt deposits are characterised by silt content of 60% - 96%, with the remainder being a mixture of sand or clay. The plasticity index of the silts is typically <12%, with a liquid limit <25%. Some samples were not plastic. The measured consolidated undrained triaxial strength was between 30kPa and 35kPa.

LIQUEFACTION ASSESSMENT OF SILTS

Liquefaction is typically associated with loose sandy deposits and the presence of significant fines is known to inhibit liquefaction. When exposed to cyclic shearing, fine (plastic) soils tend to suffer cyclic mobility due to temporarily elevated pore pressures. Silts often lie between these two behaviours. Bray and Sancio (2006) report that non-plastic silts that do liquefy then tend to dilate on shearing. They do not therefore tend to result in such significant ground movements as observed in liquefied clean loose sands.

For finer soils their susceptibility to liquefaction may be estimated according to their classification (Bray and Sancio, 2006). Bray and Sancio (2006) plot the soils on a modified Casagrande chart on which three zones are defined: ‘susceptible to liquefaction’; ‘moderately susceptible to liquefaction’; ‘not susceptible to liquefaction’. Robertson (2009) presents a method based on CPT data.

If the soils are found to be susceptible to liquefaction on account of their classification, it is necessary to undertake a conventional liquefaction assessment to investigate if they would liquefy in the design seismic event. Liquefaction potential is assessed by comparing the seismic demand, expressed as the cyclic stress ratio (CSR), with the resistance of the soil expressed as cyclic resistance ratio (CRR).

The CSR is determined from the seismic hazard being used for the design, either by calculation in the form of a site response analysis or by empirical methods, for example Idriss and Boulanger (2004). In order to get the most favourable outcome, site response analysis was used.

It is not possible to directly calculate the CRR of a soil, and whilst it can be measured in carefully controlled laboratory conditions this is difficult and expensive, so for conventional liquefaction assessments, the CRR is determined empirically from observations from previous earthquakes based on the CPT resistance or SPT values of a soil. For this project, correlations after Youd et al. (2001) were used to assess liquefaction potential based on both CPT and SPT data. In these correlations, the threshold of SPT or CPT at which liquefaction is deemed to occur is estimated from a large number of datasets, and there is therefore uncertainty (Robertson, 2009). The selected threshold is not the mean value to ensure that for most sites the assessment will be ‘safe’. Studies using probabilistic methods (for example Cetin et al. 2004) note that a deterministic Factor of Safety < 1 is approximately equivalent to a probability of liquefaction ≥ 0.85.

The results of these deterministic empirical methods are therefore not definitive. They give a strong indication of the likely behaviour of a soil, but there is some conservatism within the methodology to account for uncertainty. This is particularly the case for soils that are not clean sands, such as the Châteauguay silts (Robertson, 2004).

CONVENTIONAL LIQUEFACTION ASSESSMENT AT CHÂTEAUGUAY CUTTING

The classification data for the Châteauguay silts is plotted after Bray and Sanchio (2006) in Figure 2, which shows that the silts fall into either 'susceptible to liquefaction' or 'moderately susceptible to liquefaction' depending on the clay content of the sample. Samples plotting outside this zone have clay content which makes them not susceptible to liquefaction.

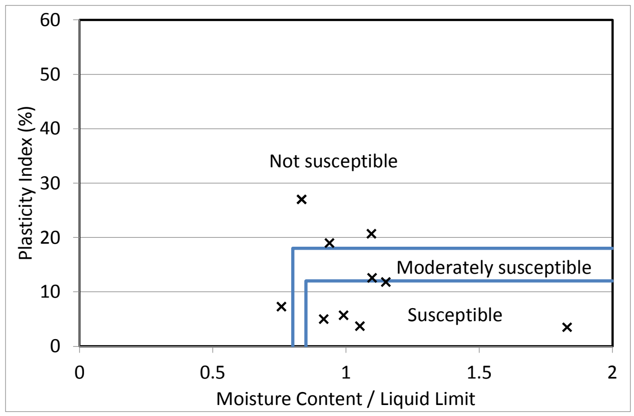

Figure 2. Liquefaction susceptibility of Champlain Silts after Bray and Sancio (2006)

Figure 3 presents two typical CPT traces for the area after Robertson (2009). The green points are 'clay-like' soils which are unlikely to liquefy, and correspond to Champlain Sea Clay. The red points are 'sand like' soils which could liquefy, and correspond to Champlain Sea Silts and some Glacial Till. There are a signficant number of points close to the boundary between these two zones, as would be expected in these soils.

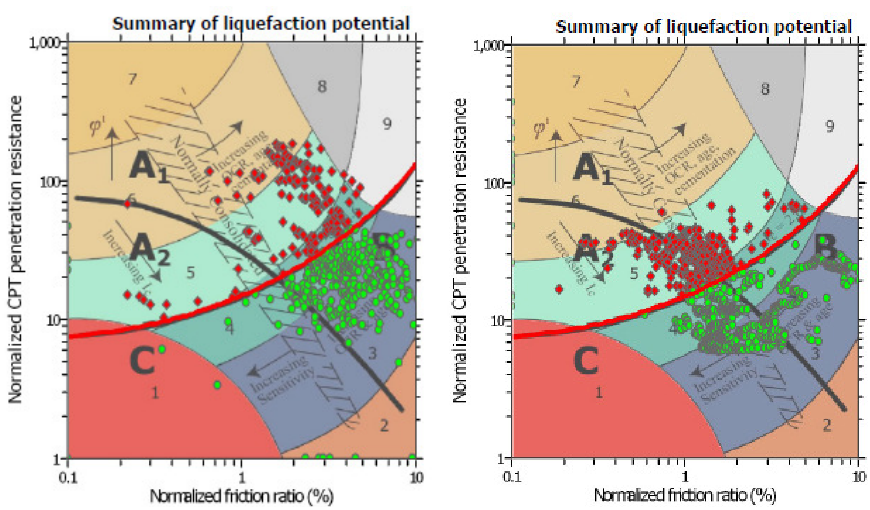

Figure 3. Liquefaction susceptibility after Robertson (2009), CLiq software, Geologismiki

Having established the possibility of liquefaction in these soils, two soil profiles were selected for site response analysis to calculate the CSR. These were at different locations along the cutting and were selected to capture the full range of stratigraphy encountered during the ground investigation. The site response was determined for six time histories, each matched to the design bedrock spectrum. Figure 3 presents the CSR profiles from these analyses. They were obtained by a one dimensional equivalent linear analyses in the frequency domain (Idriss and Sun, 1992).

The corresponding CRR at these locations was determined from the closest CPT profiles, and the SPTs from the closest boreholes (Youd et al. 2001). These data are also plotted on Figure 4.

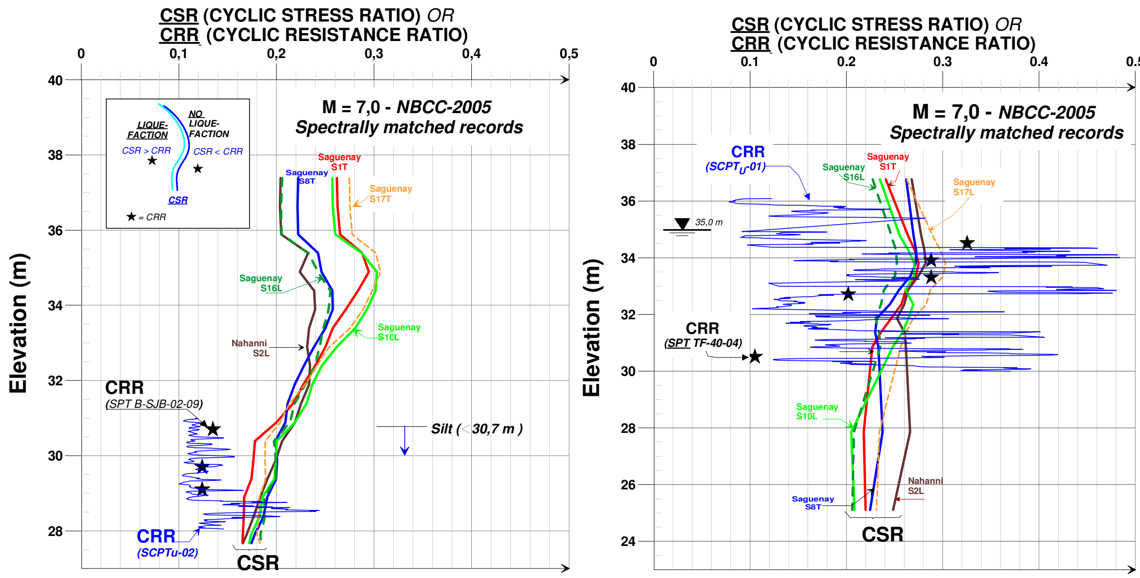

Figure 4. Results of liquefaction assessment for two typical profiles at Châteauguay

Liquefaction may be expected if the CRR is to the left of the CSR on these plots. For both profiles it was found that liquefaction was likely in the loose silt deposits at elevations above sea level of approximately 28-31m (left profile) and 30-33m and 34-36m (right profile). The CRR was also calculated following Idriss and Boulanger (2008), with the same outcome.

IMPLICATIONS OF CONVENTIONAL LIQUEFACTION ASSESSMENT AT CHATEÂUGUAY CUTTING

Although the stratigraphy of the cutting is variable, with the loose silts and clay strata being interlayered, the CPT and borehole data indicated that the potentially liquefiable materials identified by the conventional liquefaction assessment were present along the full length of the proposed cutting. It was not possible to confidently say that the liquefaction would be confined to local areas within the cutting slope. The depth at which liquefaction was identified as being possible corresponded to the base of the proposed cutting.

Once a soil has liquefied its shear strength reduces considerably, to what is often referred to as the residual shear strength. An empirical method, Stark and Mesri (1992), was used to predict the residual strength of the soils. Slope stability analyses using a lower-bound strength for the liquefied material showed that the cuttings would be unstable in the event of liquefaction occurring. The results were, however, sensitive to the value of residual strength assumed in the analyses.

Following extensive investigation of different mitigation strategies, it became clear that the cost of mitigation of the liquefaction risk was too high.

For these reasons it was considered cost-effective to attempt a programme of special sampling and testing to try and demonstrate conclusively that the silts were not susceptible to liquefaction.

SPECIAL SAMPLING

There is much information in the literature regarding the effects of sample disturbance on the results of advanced cyclic testing for liquefaction assessment (summarized in Idriss and Boulanger, 2008). Typically disturbance causes liquefaction resistance to be underestimated, but for very loose deposits disturbance can densify the sample and cause liquefaction resistance to be overestimated. Furthermore, the CPT data showed that the silt stratum was not homogeneous which makes it difficult to take a sample that is representative of the loosest material. Therefore very careful sampling was required to ensure representative and undisturbed samples of the potentially liquefiable silt were taken.

To achieve these requirements, three 200mm diameter boreholes were advanced. A 127mm (5in) diameter Osterberg Piston Sampler (ASTM, 1971) was used to take the samples. This is a form of pushed piston thin-walled-tube sampling, with the large diameter minimising the disturbance of the soil. Nine tubes were taken, in total. The full thickness of the silt stratum was continuously sampled in lengths of 900mm in this manner.

In spite of these efforts to get a sufficient amount of high-quality samples to the laboratory, it was necessary to repeat one of the boreholes since the recovery of the loose silt was poor.

The samples for cyclic testing were prepared from the Osterberg tube samples as detailed in ASTM D6528-07. The samples were very delicate on account of the low plasticity of the silt and they were prepared for testing with great care to minimise disturbance.

OBJECTIVES OF SPECIAL TESTING

There were three main objectives of the special testing. The first objective of the testing was to determine if the silts would liquefy when subjected to cyclic loading equivalent to the design seismic requirement.

Assuming that the silt did liquefy, the second objective was to establish a relationship between cyclic shear stress ratio and the number of cycles required to cause liquefaction of the silt in order to assess the likelihood of liquefaction occurring. The conventional, empirical, methods of liquefaction assessment include corrections to allow for the fines content of soils. However, they do not correct for the number of cycles required for liquefaction to occur in finer soils. Boulanger and Idriss (2007) note that the '*number of equivalent cycles to failure'* for clay-like materials is approximately three times greater than it is for sands. The potentially liquefiable silt at Châteauguay, having a very low PI does not classify as a *clay-like* material according to the definition used by Boulanger and Idriss (2007), but in reality the boundary will be less clear, and the number of cycles to failure is likely to increase gradually with increasing fines content.

The third objective of the testing was to determine the residual strength of liquefied silt to see what effect this has on the assessment of slope stability in the event that liquefaction does occur.

PROGRAMME OF SPECIAL TESTING

To ensure that the selected samples for testing included materials that were identified by the conventional CPT assessments as being liquefaction susceptible, the testing programme included classification tests, triaxial tests, consolidation tests and cyclic tests.

Cyclic testing was undertaken on the chosen samples in direct simple shear (DSScy). It is possible to perform cyclic testing in triaxial apparatus, or in ring-shear apparatus, but DSScy was selected since this most closely replicates the shearing expected in the cutting during an earthquake.

A total of nine DSScy tests were undertaken on silt samples. The samples were consolidated to their in-situ stress levels but were not pre-sheared. They were then cyclically sheared at constant volume until either the pore pressure reached the applied confining stress (indicating liquefaction); the average or cyclic shear strain reached 15%; or 1500 cycles were applied. The samples were finally subjected to static stress-controlled shearing to evaluate the post-seismic strength of the soils.

To plot the relationship for these soils between CSR and the number of cycles to 'failure', the range of CSR used in the testing programme was between 0.25 and 0.44.

RESULTS OF SPECIAL TESTING

Figure 5 presents the results of two of the DSScy tests on the Châteauguay silts, test 07 with a CSR = 0.28, and test 09 with a CSR = 0.33.

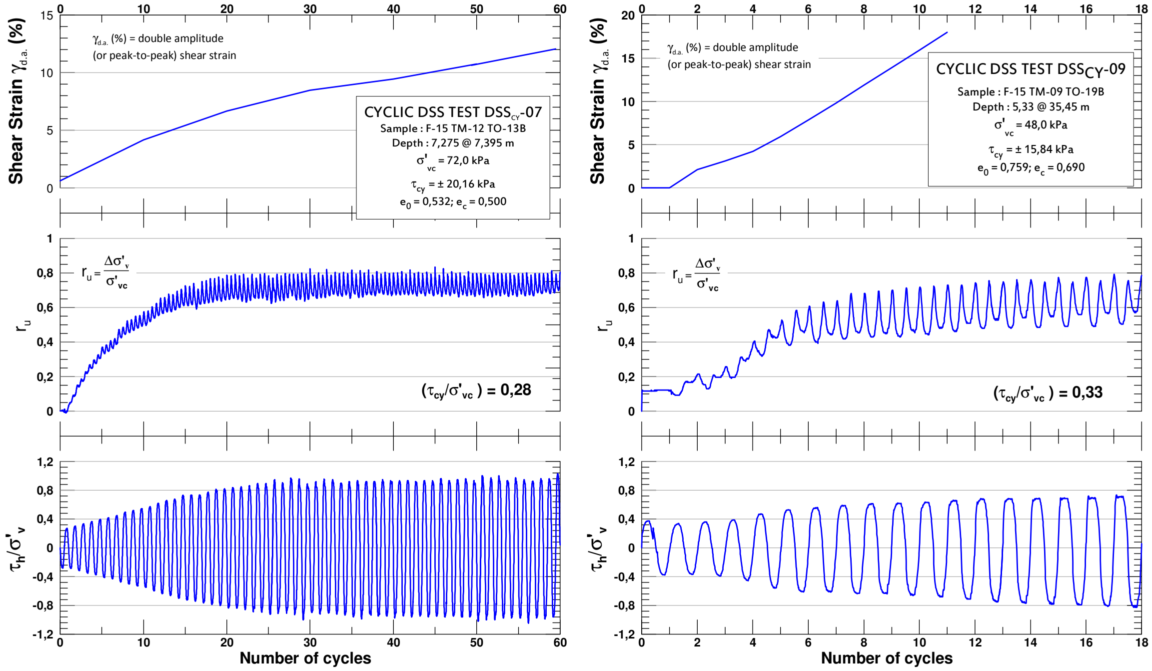

Figure 5. Results of cyclic DSS tests DSScy-07 and DSScy-09 on Châteauguay silt

In both cases the pore pressure initially increased during the cyclic shearing, but it stabilized at an average of approximately 70% of the confining stress in the sample. In neither case did the pore pressures reach 100% of the confining stress, and so there was no liquefaction. In test 07 the number of cycles required to achieve significant pore pressure increase and 5% strain was approximately 12, and the rate of increase in shear strain with more cycles was low. In test 09, 5% shear strain was reached after 5 cycles, and 10% after 7 cycles, but both tests were at CSRs significantly higher than required for design.

Figure 6 presents the summarised results of all the DSScy testing. None of the samples liquefied, but all showed high shear strains with sufficient cycles.

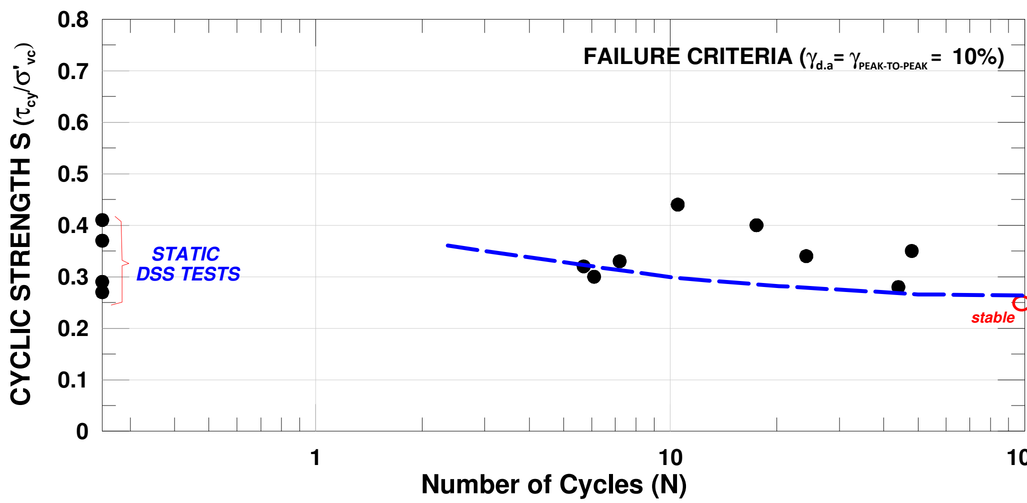

Figure 6. Cyclic strength (S-N) curve for Châteauguay silt

The calculated CSR for the cutting (Figure 3) is between 0.15 and 0.20. Extrapolation of the data form the DSScy tests indicates that at these values of CSR the number of cycles to ‘failure’ (10% shear strain) would be significantly greater than 100, probably greater than 1000. Deaggregation of the seismic hazard assessment for the project indicates the characteristic earthquake for liquefaction assessment is of Mw=7.0. Typically such an earthquake would have approximately 12 cycles of strong motion (Youd et al. 2001). Therefore at the CSR expected at the site, the anticipated cyclic shear strains will be very small.

Figure 7 presents the post-cyclic static shear test. It shows a dilatant response, with pore pressure falling. The post-liquefied strength of the soil increases from approximately 10kPa to more than 30kPa at high strain. These strengths are significantly higher than predicted by Stark and Mesri (1992) (for clean sands) and were sufficient to demonstrate the stability of the cutting.

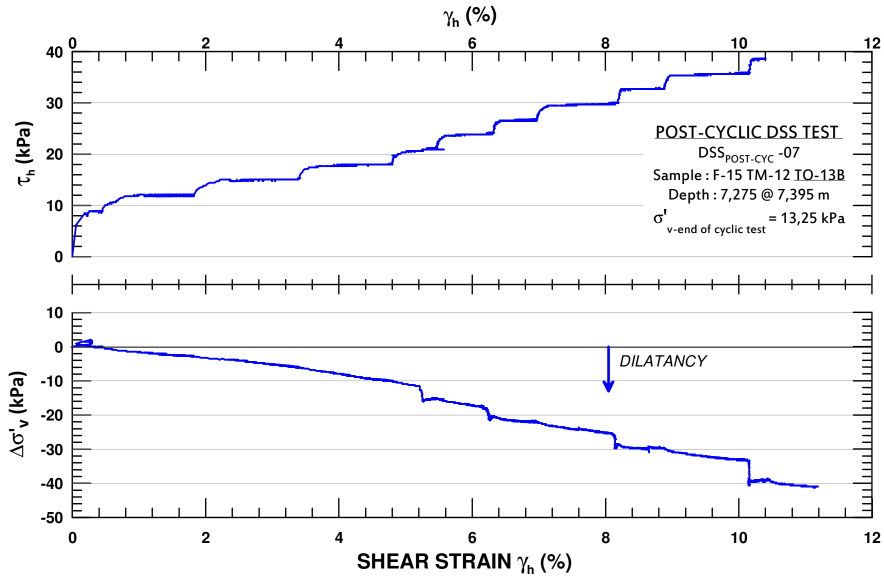

Figure 7. Results of post-cyclic DSS test DSSpost-cy-07 on Châteauguay silt (Note: no consolidation was allowed after the end of the cyclic test and the beginning of the static test)

CONCLUSION

Conventional assessment techniques indicated liquefaction susceptibility according to classification and that liquefaction was likely in the design earthquake. Special laboratory testing demonstrated that the silts were found to be susceptible to an increase in pore pressure to approximately 80% of the confining stress, with an associated loss in strength. However, it was shown that they would not liquefy and at the levels of CSR required for design, and the expected increases in pore pressure and cyclic strains would be very small. Furthermore the post-cyclic behaviour was observed to be dilatant with a consequent increase in strength, as reported likely by Bray and Sancio (2006).

This work was difficult to execute and complex, but saved a significant amount of capital expenditure on the project, whilst at the same time demonstrating the safety of the design. The conventional methods of liquefaction assessment were shown to be conservative for these soils. This may have been expected since they are empirical methods that are required to be robust for design, and because significant extrapolation is required from the conditions for which the correlations were developed to the fine soils studied in this project

REFERENCES

ASTM (1971) Sampling of Soil and Rock, ASTM STP 483, ASTM Committee D-18 on Soil and Rock for Engineering Purposes

ASTM D6528-07 “Standard test method for consolidated undrained direct simple shear testing of cohesive soils”

Boulanger, R. W., and Idriss, I. M. (2007). "Evaluation of cyclic softening in silts and clays", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 133, No.6, 641-652.

Bray JD and Sancio RB (2006) “Assessment of the Liquefaction Susceptibility of Fine-Grained Soils”, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 9

Cetin OK, Seed RB, Der Kiureghian A, Tokimatsu K, Harder LF, Kayen RE and Moss, RE (2004) "Standard Penetration Test-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE Vol. 130, No 12, 1314-1340

CLiq, 2008, Geologismiki: Geotechnical liquefaction software at http://w.w.geologismiki.gr/

Gadd, NR (1988) The Late Quaternary Development of the Champlain Sea Basin, Geological Association of Canada, Special Paper 35

Idriss IM and Boulanger RW (2004) "Semi-Empirical Procedures For Evaluating Liquefaction Potential During Earthquakes", *Proceedings of the 11th International Conference on Soil Dynamics & Earthquake Engineering and 3rd International Conference on Earthquake Geotechnical Engineering* pp 32 – 56

Idriss IM and Boulanger RW (2008) Soil Liquefaction During Earthquakes, EERI, MNO-12

Idriss IM and Sun JI (1992) "*User's Manual for SHAKE91, A computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits*", Center for Geotechnical Modelling, Dept of Civil & Environmental Engineering, University of California, Davis, Ca.

Quigley RM (1980) "Geology, Mineralogy and Geochemistry of Canadian Soft Soils: A Geotechnical Perspective", *Canadian Geotechnical Journal*, Vol 17, pp 261-285

Robertson PK (2004) "Evaluating Soil Liquefaction and Post-Earthquake Deformations Using the CPT", *Proceedings ISC-2 on Geotechnical and Geophysical Site Characterization*, Viana da Fonseca & Mayne (eds)

Robertson PK (2009) "Performance based earthquake design using the CPT" Keynote Lecture at International Conference on Performance-based design in Earthquake Geotechnical Engineering, IS Tokyo, Tsukuba, Japan.

Stark TD and Mesri G (1992) "Undrained Shear Strength of Sands for Stability Analyses", *Journal of Geotechnical Engineering,* Vol 118, No 11, 1727-1747

Youd et al (2001), "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils." *Journal of Geotechnical and Geoenvironmental Engineering*, 127_10_, 817–833.