

Evaluation of liquefaction resistance of non-plastic silt from mini-cone calibration chamber tests

C.D.P. Baxter, M.S. Ravi Sharma, N.V. Seher, & M. Jander
University of Rhode Island, Narragansett, USA

ABSTRACT: Much of Providence, Rhode Island is underlain by thick layers of non-plastic silt and it is important to know if the existing field-based liquefaction potential evaluations (Youd et al. 2001) are accurate. The objective of this research was to critically evaluate the applicability of CPT-based liquefaction approaches to the Providence silts. This was accomplished through a laboratory testing program involving mini-cone calibration chamber and cyclic triaxial tests. A 1 cm² piezo-cone was inserted into the center of 45 cm diameter samples of silt prepared by a modified moist tamping method. All the samples were isotropically consolidated to 100 kPa prior to cone testing. Ten tests on saturated and unsaturated specimens of Providence silt were conducted to determine a relationship between relative density and tip resistance. These results were combined with a cyclic resistance - relative density relationship obtained from a previous study, and a new relationship between cyclic resistance ratio and tip resistance for Providence silt was developed. The new relationship was compared to field based approaches proposed by Robertson & Wride (1998) and Moss et al. (2006). There was reasonable agreement between the approaches which supports the use of the existing field-based CPT methods for assessing the liquefaction potential of non-plastic silts.

1 INTRODUCTION

Field based approaches are typically used to relate the cyclic resistance of soils with *in situ* tests such as the standard penetration test (SPT) and the cone penetration test (CPT). In these methods, penetration test data from sites where earthquakes have occurred are plotted against the estimated cyclic stress caused by the earthquake, and a line is drawn separating data where liquefaction did or did not occur (see Youd et al. 2001). In all the field based approaches, corrections are applied to account for soils with varying amounts of fines, typically up to 35%.

Many of the coastal areas surrounding Providence, Rhode Island are underlain by thick deposits of loose, non-plastic silts with fines contents greater than 95%. As such, there is considerable uncertainty in the literature about the applicability of the field based approaches when dealing with pure silts. Recently, there have been several studies performed at the University of Rhode Island (URI) to address this issue, including an evaluation of disturbance during sampling (Page 2004), sample prepara-

tion methods for laboratory testing (Bradshaw and Baxter 2007), the development of a soil-specific relationship between shear wave velocity and cyclic resistance (Baxter et al. 2008), and a detailed site response and liquefaction analysis for a site in downtown Providence (Bradshaw et al. 2007a; Bradshaw et al. 2007b).

The primary implications of the URI work are that existing SPT and CPT based approaches, as outlined in Youd et al. (2001), provide reasonable predictions of cyclic resistance of non-plastic silt when the recommended fines content corrections are applied. The SPT methods in general yield the most conservative results. In addition, it was found that the relationship between shear wave velocity and cyclic resistance is soil specific, and field based approaches using shear wave velocity should not be used.

The objective of this study was to continue to evaluate the applicability of CPT based approaches for evaluating the cyclic resistance of Providence silts. This was accomplished through a laboratory testing program involving mini-cone calibration chamber and cyclic triaxial tests. A mini-cone calibration chamber was built for this study and used to determine a relationship between relative density and tip resistance for the silt (Seher 2008). Results of cyclic triaxial tests performed by Bradshaw (2006) were used to establish a relationship between cyclic resistance and relative density. Combining these two relationships, a laboratory based liquefaction curve for the CPT was generated specifically for the Providence silts.

2 MINI-CONE CALIBRATION CHAMBER TESTING PROGRAM

A mini-cone calibration chamber was designed and built to test 45 cm diameter samples of non-plastic silt using a 1 cm² piezocone. The mini-cone was built by FUGRO Engineers B.V., Netherlands, and consisted of two, 5 kN load cells connected in series to measure the tip and sleeve resistance and a 10 MPa pore pressure transducer mounted on the shoulder of the cone tip (i.e. the u_2 position). The chamber was modeled after a triaxial cell in that samples were encased in a rubber membrane and consolidated isotropically (i.e. BC1 boundary conditions). Back pressure saturation was used for some of the tests. Photographs of an exposed sample, a sample encased in a rubber membrane, and the sealed calibration chamber are shown in Figure 1. Details of the design and construction of the chamber and calibration of the instruments can be found in Franzen (2006), Jasinski (2008), and Seher (2008).

The mini-cone was mounted in the baseplate of the chamber and pushed upwards into the sample using a hydraulic piston. The penetration rate was controlled with a needle valve and measured using a linear displacement transducer manufactured by Celesco™. The penetration rate for all the tests ranged from 1.81 to 2.5 cm/s, with an average rate of 2.05 cm/s.

2.1 *Properties of Soil Tested and Sample Preparation Methodology*

The Providence silts were deposited as proglacial lake sediments during the last glacial retreat (Murray 1988). The silts are angular in shape and were deposited as a sequence of seasonal varves, with alternating finer-grained layers in winter and coarser-grained layers in summer.

The silts tested in this study were obtained from three sites located in the Providence area (Bradshaw 2006) and were blended together to obtain the necessary amount of soil for calibration chamber testing. A summary of their geotechnical

properties is given in Table 1. The Atterberg Limits of the silts could not be determined, and thus the silts are considered to be “non-plastic”. The silts are classified as ML according to the Unified Soil Classification System (USCS).

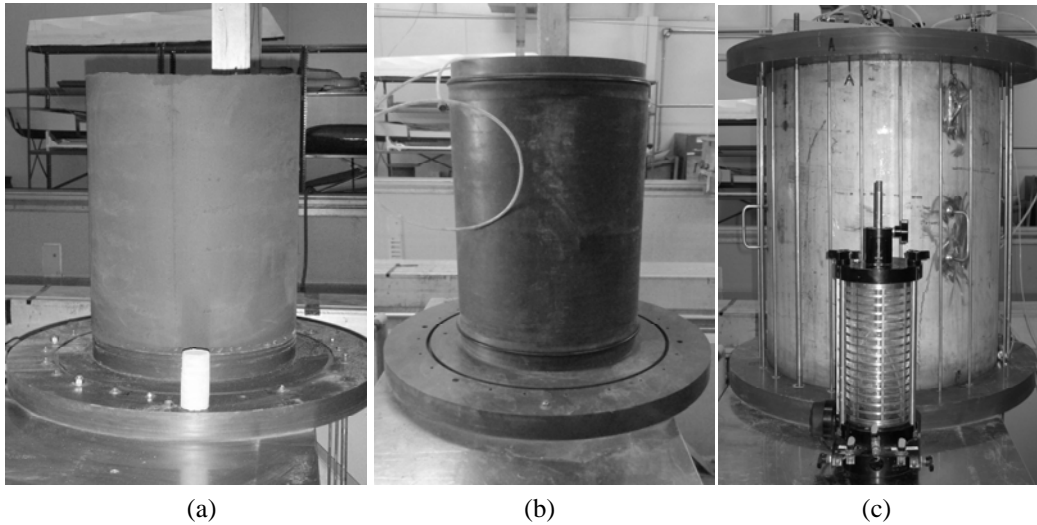


Figure 2. a.) 45 cm diameter, 56 cm high sample of non-plastic silt after sample preparation, b.) the sample encased in a rubber membrane, and c.) the sealed chamber prior to application of cell and back pressure (a standard triaxial cell is shown for scale).

Table 1. Properties of the silts used in this study (Seher 2008).

Soil	Specific Gravity	% < 0.074 mm	% < 0.005 mm	D ₅₀ (mm)	Maximum Void Ratio ^a	Minimum Void Ratio ^b
Providence Silt	2.75	98	17	0.013	1.15	0.59

a. Maximum void ratio determined by placing a slurry and allowing it to settle in a graduated cylinder.

b. Minimum void ratio determined from a modified compaction test (ASTM D 1557).

Samples were prepared using a moist tamping method (Ladd 1978). In this approach, samples are compacted in layers, and either the compactive effort or layer density is adjusted for each layer to achieve uniform samples. Bradshaw and Baxter (2007) showed that the molding water content used during tamping has a significant influence on the cyclic resistance of silts. The strengths of samples tamped at an initial saturation (*S*) of about 55% matched the strengths of both normally consolidated samples prepared from a slurry, as well as overconsolidated specimens trimmed from a block sample of Providence silt. At lower molding water contents, however, the cyclic resistance was significantly higher due to differences in fabric. Therefore, all the samples tested in this study (both the mini-cone tests and the cyclic triaxial tests) were prepared to an initial degree of saturation of 55%.

3 RESULTS OF MINI-CONE CALIBRATION CHAMBER TESTS

The results of the 10 mini-cone calibration chamber tests are summarized in Table 2. Relative densities of the samples ranged from 30% to 85%, and all the samples were consolidated isotropically to an effective stress of 100 kPa. Six samples were saturated using a back pressure of 300 kPa, and four samples were tested at the molding water content (i.e. unsaturated). Based on measured mini cone pore pressures for the

saturated tests and good agreement between measured penetration resistances of the saturated and unsaturated samples, it is believed that the penetration tests occurred under drained conditions. Also shown in Table 2 are the average tip resistance (q_c), sleeve friction (f_s), and friction ratio (R_f) for each test. These values were obtained by averaging the cone data from 10 to 45 cm within the samples.

Figure 3 shows detailed results from the test performed on a sample prepared to a relative density of 61%. The plots of tip and sleeve resistance show some variation corresponding to the layers formed during compaction of the samples, but are otherwise fairly uniform. The pore pressure response during penetration was approximately 300 kPa, which was the back pressure used in this test. The relative density of the sample was calculated from the overall volume and mass of the sample as well as from the measured density of each layer during compaction. Small constant volume “plug” samples were taken at several depths following cone testing to verify the density measurements.

Table 2. Summary of mini-cone penetration test results.

Relative Density (%)	q_c (MPa)	f_s (MPa)	R_f (%)	Cell Pressure (MPa)	Back Pressure (MPa)	Effective Stress (MPa)
30	2.16	0.022	1.02	0.1	0	0.1
30	1.45	0.015	1.03	0.4	0.3	0.1
50	4.83	0.047	0.98	0.1	0	0.1
58	4.97	0.048	0.96	0.4	0.3	0.1
60	5.72	0.067	1.17	0.1	0	0.1
61	2.25	0.021	0.92	0.4	0.3	0.1
65	6.08	0.047	0.78	0.4	0.3	0.1
77	8.09	0.081	1.00	0.4	0.3	0.1
84	18.45	0.144	0.78	0.1	0	0.1
85	15.56	0.136	0.87	0.4	0.3	0.1

4 SOIL SPECIFIC CRR- q_c RELATIONSHIP

Figure 4 shows the relative density-tip resistance relationship derived from the 10 mini-cone calibration chamber tests. Since the effective stress for all tests was 0.1 MPa (i.e. 1 atm), $q_c = q_{c1}$. Error bars are included on each data point to illustrate the variation in measured tip resistance and relative density observed in each test.

Figure 5 shows the relationship between cyclic resistance and relative density for the Providence silts (Bradshaw, pers. comm.). Bradshaw (2006) performed cyclic triaxial tests on the Providence silt from three different sites in Rhode Island, and the silts from two of these sites were blended together for the calibration chamber tests. Samples were prepared using moist tamping at an initial saturation of 55% (Bradshaw & Baxter 2007) and were isotropically consolidated to an effective stress of 100 kPa. The relative densities of the samples tested ranged from 42 to 83%. The cyclic resistance ratio (CRR), defined as the shear stress required for liquefaction divided by the effective confining stress, was determined using 5% double amplitude strain as the failure criterion, and the CRR corresponding to 15 cycles to failure was considered to be equivalent to the CRR for a magnitude 7.5 earthquake. The results were corrected for field stress conditions assuming $K_o=0.45$ (Baxter et al. 2008).

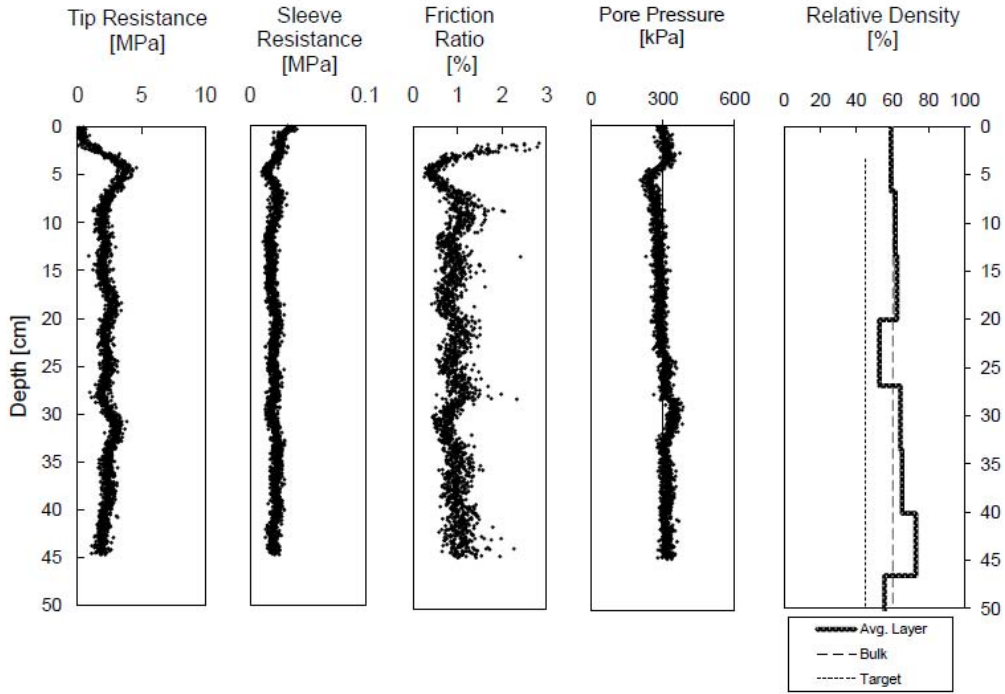


Figure 3. Mini-cone calibration test results for a sample of Providence silt prepared to a relative density of 61%.

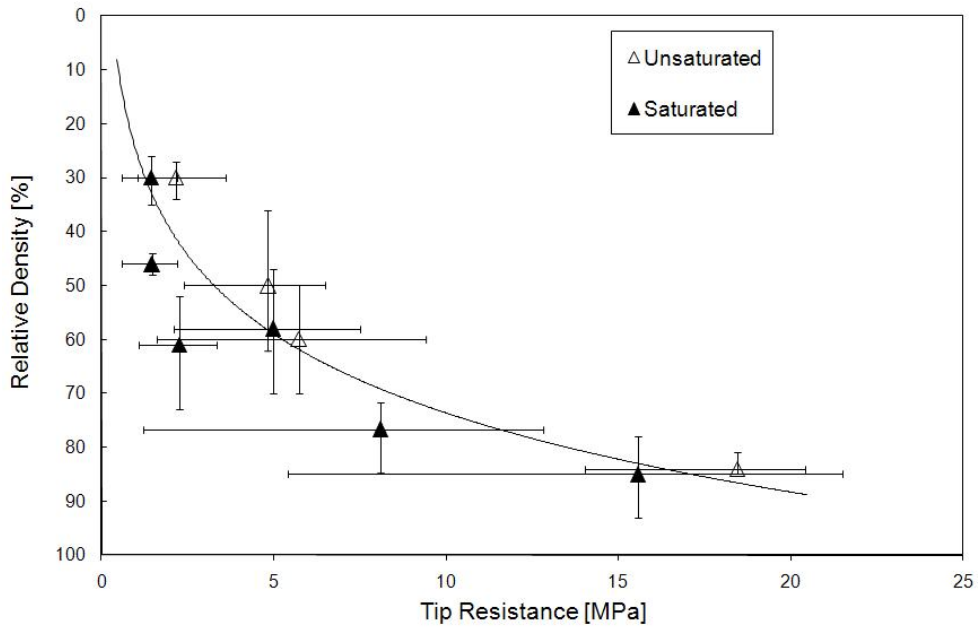


Figure 4. Relative density-tip resistance relationship from the mini-cone calibration chamber tests.

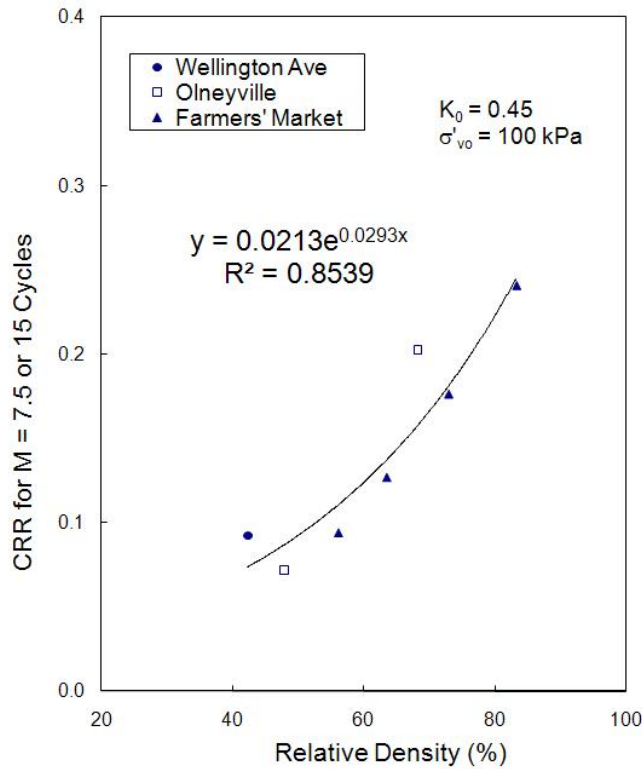


Figure 5. Relationship between cyclic resistance ratio and relative density from cyclic triaxial tests for the Providence silts used in this study.

Using relative density as the link between the calibration chamber and cyclic triaxial test results, the cyclic resistance corresponding to the measured tip resistances in Table 2 were calculated using the equation shown in Figure 5. These results are shown in Figure 6.

5 COMPARISON WITH EXISTING FIELD BASED APPROACHES

The Providence silt-specific relationship developed from the mini-cone calibration chamber and cyclic triaxial tests was compared to two existing field based liquefaction approaches from the literature. The approach developed by Robertson and Wride (1998) is widely used and is considered to be the state-of-the practice (Youd et al. 2001). Moss et al. (2006) proposed a probabilistic approach for assessing liquefaction resistance from cone data.

Both methods require normalizing q_c to an in situ vertical effective stress of 1 atm (i.e. q_{c1}) in order to estimate the CRR. This creates an issue because the calibration chamber tests were consolidated isotropically, which is generally not representative of in situ conditions. Because q_c is known to be primarily a function of horizontal effective stress (and relative density), it was assumed that the calibration chamber test results performed at an isotropic stress of 100 kPa were equivalent to in situ tests at a vertical effective stress of 222 kPa and a horizontal effective stress of 100 kPa (i.e. $K_0 = 0.45$). Thus, the q_c values in Table 2 were normalized using 222 kPa, and the resulting estimated CRR values from each method are shown in Figure 6.

There is reasonable agreement between the existing field based approaches and the results of the laboratory based study. This is encouraging for sites where the fines content is significantly greater than 35%, and the implications of this study are that the existing CPT-based approaches developed by Robertson and Wride (1998) and Moss et al. (2006) provide reasonable predictions of the cyclic resistance of non-plastic silt when the recommended fines content corrections are applied.

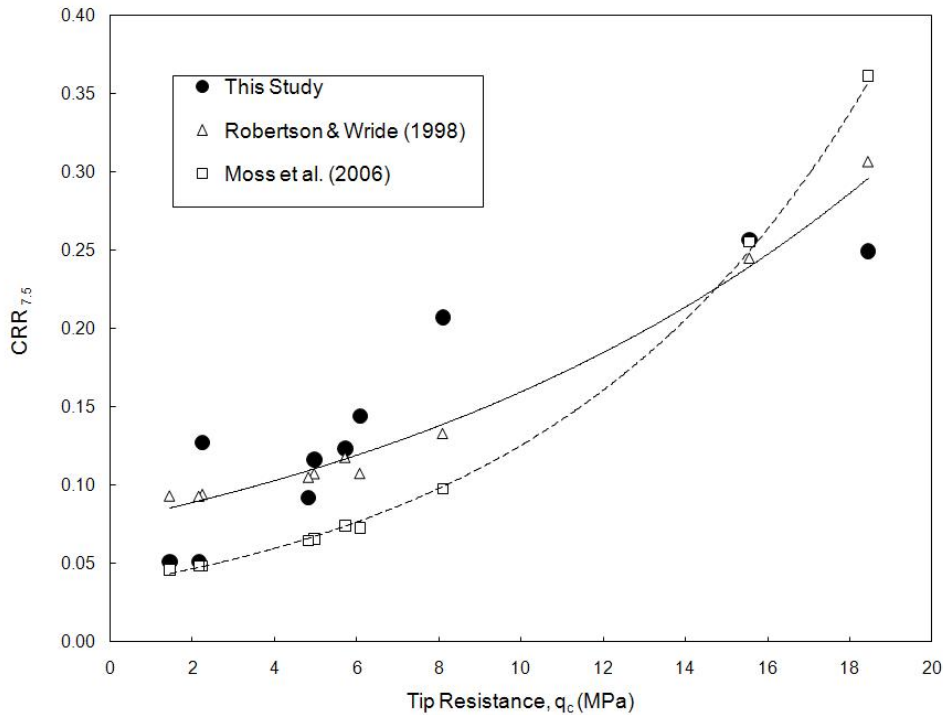


Figure 6. Comparison of liquefaction resistance curves for Providence silt from mini-cone calibration chamber and cyclic triaxial tests (this study) and published field based methods.

6 CONCLUSIONS

The objective of this paper was to critically evaluate the applicability of CPT-based liquefaction resistance approaches to non-plastic silts commonly found in Rhode Island. Ten mini-cone calibration chamber tests on saturated and unsaturated specimens of Providence silt were conducted to determine a relationship between relative density and tip resistance. These results were combined with a cyclic resistance - relative density relationship obtained from a previous study, and a new relationship between cyclic resistance ratio and tip resistance for Providence silt was developed. The new relationship was compared to field based approaches proposed by Robertson and Wride (1998) and Moss et al. (2006). There was reasonable agreement between the approaches which supports the use of the existing field-based CPT methods for assessing the liquefaction potential of non-plastic silts.

7 ACKNOWLEDGEMENTS

Financial support for the work presented in this paper was provided by the Rhode Island Department of Transportation. Jan-Hendrik Franzen and Jeffrey Jasinski designed and constructed the calibration chamber. Their support is acknowledged with thanks and appreciation.

8 REFERENCES

- Bradshaw, A. 2006. Liquefaction Potential of Non-Plastic Silt. *Ph.D. Dissertation*, University of Rhode Island.
- Bradshaw, A. & Baxter, C. 2007. Sample preparation of silts for liquefaction testing. *Geotechnical Testing Journal*, 30:1-9.
- Bradshaw, A.S., Green, R.A., and Baxter, C.D.P. 2007a. A Rational Approach for Evaluating Seismic Demand and Resistance at a Silt Site in Rhode Island, *Boston Society of Civil Engineers' Civil Engineering Practice Journal*, 22(1): 5-18.
- Bradshaw, A.S., Baxter, C.D.P., and Green, R.A. 2007b. A Site-Specific Comparison of Simplified Procedures for Evaluating Cyclic Resistance of Non-Plastic Silt, *GeoDenver 2007, Geotechnical Special Publication 160*.
- Franzen, J.-H. 2006. Cone penetration resistance in silt. *M.S. Thesis*, University of Rhode Island.
- Jasinski, J. D. 2008. Mini cone chamber testing of silt. *M.S. Thesis*, University of Rhode Island.
- Ladd, R.S. 1978. Preparing test specimens using undercompaction, *Geotechnical Testing Journal*, 1(1):16-23.
- Moss, R., Seed, R. B., Kayen, R., Stewart, J., Der Kiureghian, A., & Cetin, K. 2006. CPT based probabilistic and deterministic assessment of in situ seismic soil liquefaction potential. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(8):1032-1051.
- Murray, D. 1988. Rhode Island: The Last Billion Years. Department of Geology, University of Rhode Island.
- Page, M. 2004. An Evaluation of Sample Disturbance and Strength Parameters of Rhode Island Silts, *M.S. Thesis*, University of Rhode Island.
- Robertson, P. K. & Wride, C. 1998. Evaluating cyclic liquefaction potential using the cone penetration test. *Canadian Geotechnical Journal*, 35:442-459.
- Seher, N. 2008. Mini-Cone Chamber Testing and Liquefaction of Silt, *M.S. Thesis*, University of Rhode Island.
- Youd, T.L., 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.