Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-2-7

Assessment of ground improvement on silt based on spatial variability analysis of CPTU data

H.F. Zou, G. J. Cai, S.Y. Liu & J. Lin
Jiangsu Key Laboratory of Urban Underground Engineering and Environmental Safety, Southeast University, Nanjing, Jiangsu, China

T.V. Bheemasetti & A.J. Puppala
The University of Texas at Arlington, Arlington, Texas, USA

ABSTRACT: A novel resonance deep compaction technique was used to improve the strength and density of loose saturated silts in northern Jiangsu Province, China. In this research, the random field theory is applied in modeling the characteristics of the cone tip resistance (q_t) obtained from the piezocone penetration tests to evaluate the performance of the compaction improvement. The three random field model parameters including the mean value, vertical scale of fluctuation and coefficient of variation of the q_t data before and after the compaction are analyzed. It is shown that the mean values and scales of fluctuation of q_t decrease immediately after the compaction but then they increase as the density of the silt recovers. The coefficient of variation consistently decreases with respect to the recovery age. These observations demonstrate the successful application of the resonance compaction in improving the stiffness and homogeneity of the silt.

1 INTRODUCTION

Ground improvement techniques have been widely used to increase the density, strength and stiffness of saturated loose sands and silts (Massarsch & Fellenius 2002, 2005). Assessing the performance of ground improvement is a major task and can be achieved using either in situ or laboratory tests. In routine projects, assessment of improvement effect based on laboratory tests suffers the disadvantages of high cost, long testing period and difficulty in obtaining the representative undisturbed cohesionless soil samples. Therefore, in situ tests have been widely applied.

The modern advanced piezocone penetration test (CPTU) has been accepted as one of the most useful tools for assessing the quality of ground improvement (Lunne et al. 1997; Ku & Juang 2011). The CPTU provides three separate readings, total cone tip resistance (q_t) simultaneously with sleeve frictional resistance (f_s) and pore water pressure (u), and offers near continuous and economical information about the in situ subsurface stratification (Cai et al. 2011, 2012). The q_t and f_s indices represent the failure strength and density of cohesionless soils, while the u measurements describe the flow characteristics. However, most traditional application of CPTU for the quality control either only took the mean soil properties into consideration or compared the soil property records in a qualitative sense (e.g. Lunne et al. 1997; Ku & Juang 2011). The impact of ground improvement on the spatial variability of soil is not considered in above studies.

This paper performs spatial variability analysis on the CPTU data obtained from a silt site located in the floodplain of abandoned Yellow River in Jiangsu province, China. The silts were enhanced using a new deep resonance compaction technique to increase the liquefaction resistance of the silt. In this study, the random field theory (RFT) is applied to model the spatial variability of the CPTU cone tip resistance of the silts and to assess the performance of compaction. To achieve this study, the theory of random field is briefly summarized first. Then the site information, resonance vibratory compaction technique, and also the piezocone penetration tests are introduced. The variations of the RFT model parameters of the q_t data are analyzed to illustrate the performance of the compaction.

2 RANDOM FIELD MODEL

The spatial variability of a soil property can be modeled as a zero-mean weakly stationary random field (Uzielli et al. 2005). Despite of measurement error associated with the CPTU data, the measured q_t profile is expressed as the linear combination of a trend and fluctuation component about the trend:

$$g(z) = t(z) + x(z) \tag{1}$$

in which $g(z)$ = measured q_t at location z; $t(z)$ = trend function at z; $x(z)$ = fluctuation component or residual at z; and z = depth coordinate in this research.

The trend is generally determined using the ordinary regression analysis. Extensive researches on the selection of trend function revealed that the trend functions should be simple but still doing justice to the data (e.g. Baecher & Christian 2003; Uzielli et al. 2005; Stuedlein et al. 2012). In this research it is found that a linear trend function is sufficient to describe the deterministic component within the q_t data and hence is adopted.

The fluctuation component, $x(z)$, represents the spatial variability of a soil property. Two parameters including the scale of fluctuation (δ) and coefficient of variation (COV) are used to describe the fluctuation component. The δ provides an indication of the distance within which the property values show relatively strong correlation, whereas the COV provides the magnitude of variation (Phoon & Ching 2012). The COV is defined as:

$$COV = \frac{\sigma}{t_M} = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left[x(z_i)\right]^2}}{t_M} \tag{2}$$

where σ = standard deviation; t_m = mean of q_t; n = number of data points; z_i = depth coordinate of ith sampling point.

Several methods have been developed to estimate δ (e.g., DeGroot & Baecher 1993; Jaksa et al. 2000; Phoon et al. 2003; Vanmarcke 2010). The method of moments is simple and accurate to achieve this estimation. In this method, the sample autocorrelation function (ACF) representing the strength of the autocorrelation with respect to the lag distance between two observations are calculated. Then a theoretical autocorrelation model (ACM) is fitted to the ACF to provide a continuous description of the spatial autocorrelation. The δ is estimated from the model parameter of ACM. The ACF is estimated using the following approximation (Phoon et al. 2003):

$$R(\tau = j\Delta z) \approx \frac{1}{s^2(n-j-1)}\sum_{i=1}^{n-j}\left[x(z_i)x(z_{i+j})\right] \tag{3}$$

where Δz = sampling interval and Δz = 0.05 m in this research; n = number of data points; s^2 = sample variance [evaluated from Equation (3) using j = 0 with $R(0) = 1$].

Equation (3) is only accurate up to 1/4 length of the record. To further improve the accuracy of the curve fitting, it has been suggested that only the data points with autocorrelation coefficients larger than the Bartlett's limit (r_B) should be used (Uzielli et al. 2005). The Bartlett's limit is given by $r_B = 1.96/\sqrt{n}$.

Several ACMs have been presented in geotechnical literatures (Uzielli et al. 2005; Stuedlein et al. 2012). Four theoretical autocorrelation models (ACM) along with the estimates of scale of fluctuation have been widely used in geotechnical literatures, as shown in Table 1. These autocorrelation models include the single exponential (SNX), cosine exponential (CSX), second-order Markov (SMK), and squared exponential (SQX). These four ACMs are sufficient for the curve fitting in the estimation of δ. The ACM providing best fit to the ACF should be used to represent the actual autocorrelation structure of soil property. The best fit can be determined as providing the largest coefficient of determination (R^2) in the curve fitting.

Table 1. Common ACMs and corresponding scale of fluctuation (Phoon et al. 2003)

ACM	Mathematic expression	Scale of fluctuation (δ)
SNX	$R(\tau) = \exp(-\lambda\lvert\tau\rvert)$	$\delta = 2/\lambda$
CSX	$R(h) = \exp(-b\lvert h\rvert)\cos(bh)$	$\delta = 1/b$
SMK	$R(h) = (1+d\lvert h\rvert)\exp(-d\lvert h\rvert)$	$\delta = 4/d$
SQX	$R(h) = \exp[-(ah)^2]$	$\delta = \sqrt{\pi}/a$

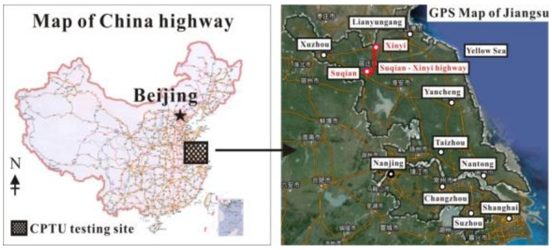
An important assumption of the random field theory is that the fluctuation component is weakly stationary. The weak stationarity assumes that the mean and variance are constant along space, and that the autocorrelation structure only depends on the lag distance between the observations. The weak stationarity can be checked using the modified Bartlett's statistics test proposed by Phoon et al. (2003). However, this test is generally too strict for soil data in practice (e.g. Stuedlein et al. 2012). The geotechnical evidence of the weak stationarity of soil data is the homogeneity of a soil unit. If the fluctuation component of q_t data is collected from a homogeneous soil unit, then it can be considered as a weak stationary random field in a qualified sense. Therefore, in this study the weak stationarity is not tested rigorously because only the q_t data corresponding to the middle silt will be studied, whereas the non-stationarity induced by the scattered soil seam will be neglected. Before applying the random field theory, the site conditions and testing program will be presented in the subsequently section.

3 SITE CONDITIONS AND TESTINGS

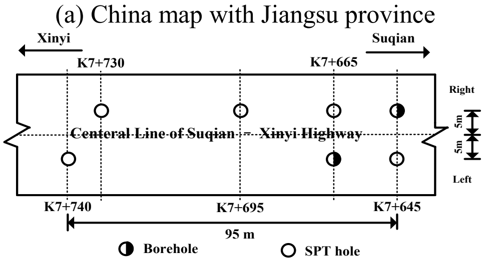
In this section, the main physical properties of the subsoil determined from laboratory tests are introduced first. To increase the density and liquefaction resistance of the subsoil, a novel vibratory compacting technique is applied. Four sets of piezocone penetration tests are performed in the testing site both before and after the improvement. Using these tests, the performance of the ground improvement technique on the site is then analyzed and discussed.

3.1 *Geological conditions*

The testing site is located at the Suqian-Xinyi highway in Suqian, northern Jiangsu Province, China. The sediments at this site mainly consist of silt and silty sand. A test section with 95 m in length and 20 m in width at the highway site was chosen to investigate the performance of a new resonance compaction technique. Locations of the highway and test section are shown in Figure 1.



(a) China map with Jiangsu province



(b) Testing section

Figure 1. Location and layout of testing site

Quaternary sediments form the soil stratigraphy in the upper 20 m depth beneath the embankment surface. The uppermost soil unit is a sandy silt unit with scattered silty clay seams. The followed soil layer is a loose silt (upper silt) unit with silty sand and silty clay seams. A loose silt unit (middle silt) with thin silty sand seams is located just beneath the upper silt unit. The lower soil unit is a median to dense silt with scattered silty sands interlayer. Main physical characteristics of the subsoil including the specific gravity (G_s), clay content (CC), moisture (w), liquid limit (LL), and plasticity index (PI) are presented in Table 2, according to results of laboratory tests on collected disturbed soil samples. The ground water table location is about 3.8 to 5.5 m below the ground surface. The middle silt is the major concern of the improvement and is considered in this study.

Table 2. Main physico characteristics of soils

Stratum	Depth (m)	G_s	CC (%)	w (%)	LL	PI
Sandy silt	0 – 2.0	2.74	8.62	11.4	26.2	8.8
Upper silt	2.0 – 6.5	2.70	6.34	25.8	28.9	7.0
Middle silt	6.5 – 16.0	2.69	7.59	29.5	28.4	5.8
Lower silt	16.0 – 26.4	2.68	8.57	27.6	27.5	4.5

3.2 *Resonance compaction*

A new resonance compaction technique is developed for increasing the density and strength of the cohesionless soils by Southeast University, China. Figures 2(a) and 2(b) show a schematic of the resonance compaction equipment along with the details of the compaction probe. The resonance compaction points are set in a triangular manner as shown in Figure 2(c). The spacing interval for two adjacent compaction points is 1.5 to 2.0 m.

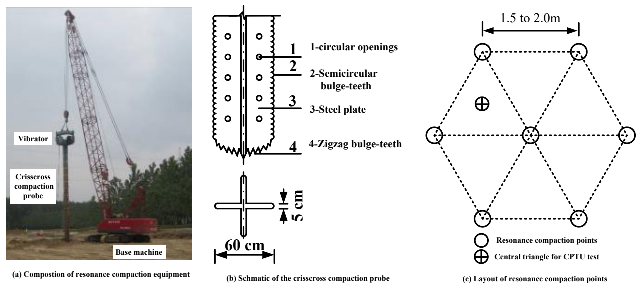


Figure 2. Schematic and specification of the resonance compaction

The compaction equipment consists of a vibrator with a powerpack, a compaction probe and a base machine. The compaction probe is inserted into the ground under the control of vibrator. The compaction probe transmits the energy provided by the vibrator to the sounding soils. The most effective energy transfer occurs when the compaction probe is allowed to operate at the resonance frequency, which is determined according to pre-compacting tests. The resonance compaction probe in this research is a crisscross section vibratory probe of 15 m in length and 0.6 m in width. To reduce probe impedance and increase the drainage of excess pore water pressure induced by the compaction, circular openings of 0.1 m in diameter are spaced at 0.8 m along the probe. To evaluate the performance of the compaction, several CPTU tests have been performed in this testing section and will be introduced subsequently.

3.3 *Piezocone penetration test*

The CPTU system consists of a hydraulic pushing and leveling system, 1-m length segmental rods, cone penetrometers and a data acquisition system. The 10 cm^2 piezocone has a sleeve area of 150 cm^2 with a pore pressure transducer located 5 mm behind the base (u_2 configuration). All CPTU tests were conducted at a penetration rate of 2 cm/sec, and measurements were collected every 5 cm.

Piezocone penetration tests were performed at the testing section for four times, one set before the compaction and the other three sets after the compaction. The first set of CPTU tests was performed on the soil before compaction and consisted of 17 soundings to provide the referential background of site information. Later the resonance compaction was conducted at the testing section. The second set of CPTU tests was performed on the soils after 14 days of recovery and consisted of 9 soundings. The third set of CPTU tests was performed after 54 days of recovery and consisted of 7 soundings at the center of the triangle of three adjacent compaction points (as shown in Fig. 2(c)). The fourth set of CPTU tests were performed after 60 days of recovery and consisted of 10 soundings. The layouts of these CPTU soundings are shown in Figure 3. All the CPTU soundings were performed either along or adjacent to the central line of the highway. Representative CPTU profiles are illustrated in Figure 4.

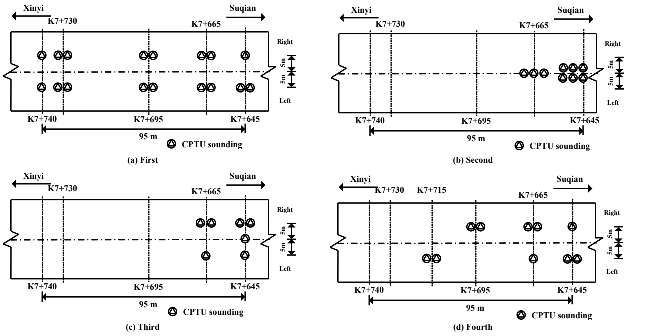


Figure 3. Layout of four sets of CPTU soundings of: (a) First; (b) Second; (c) Third; (d) Fourth dataset

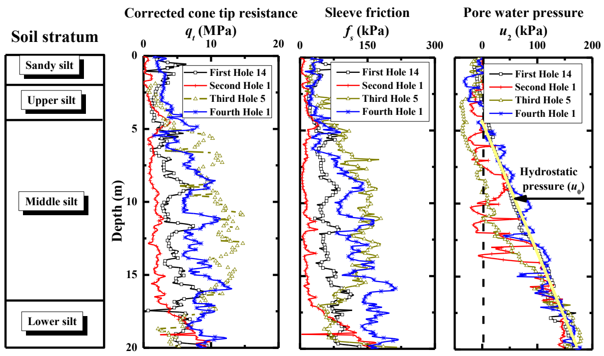


Figure 4. Typical CPTU profiles at the Suqian site for the four CPTU data sets

4 VERTICAL RANDOM FIELD MODEL PARAMETERS

Literature revealed that the spatial variability of a soil property is generally anisotropic, mainly reflected in the much higher spatial autocorrelation in the horizontal direction compared to that in the vertical direction. Due to the limitation of the sample volume in the horizontal direction, this research mainly focuses on the vertical spatial variability. The random field model parameters including mean value, COV and the vertical scale of fluctuation (δ_V) of the q_t data before and after the compaction will be analyzed. Based on the results, the performance of the resonance compaction technique in improving the density of the silt is discussed.

4.1 *Interpretation of vertical scale of fluctuation*

The estimate of vertical scale of fluctuation is impacted by the trend removal procedure which is applied to generate the stationary random field. In this section, two types of analyses are conducted to describe the variation of the spatial autocorrelation of q_t with respect to the ground improvement. In the first type of analysis (denoted as generic analysis hereafter), a generic two-dimensional trend is removed from all the q_t data of each dataset using the ordinary linear regression analysis. In the second type of analysis (denoted as specific analysis), a specific one-dimensional linear trend is removed from each q_t profile of each dataset. Then the fluctuation component of each q_t profile is determined by measured profile subtract the corresponding trend.

Figure 5 presents the estimated sample ACFs of all fluctuation components of q_t records for each dataset in the generic analysis. To obtain a generic estimate of the vertical scale of fluctuation, the ACFs of each corresponding dataset at each lag distance are averaged. The averaged ACFs are then used for estimating the generic δ_V. Using the inserting Bartlett's limit method (BLM) proposed by Jaksa et al. (2000), the horizontal Bartlett's line of $r_B = 1.96/\sqrt{n}$ is superimposed on the ACF plots. Then the lag distance corresponding to the intersection between the Bartlett's line and the sample ACFs approaches the estimate of the vertical scale of fluctuation. The ACFs, averaged ACFs, fitted ACM and statistics including the measurement interval, Bartlett's limit, number of ACF data points, estimates of generic δ_V and the coefficient of determination (R^2) are all presented in Figure 5.

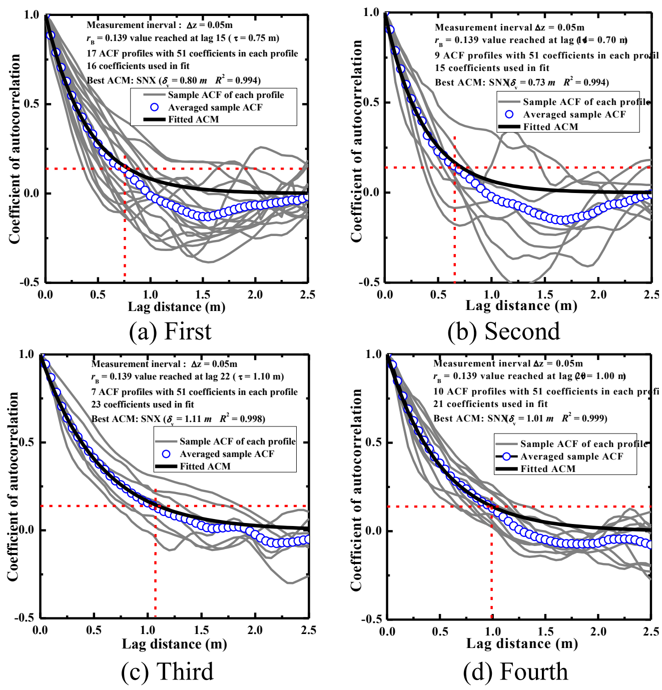


Figure 5. Estimates of vertical scale of fluctuation using generic analysis for: (a) First; (b) Second; (c) Third; (d) Fourth dataset

It can be seen from Figure 5 that before compaction, the generic δ_v of q_t data of the middle silt is 0.80 m. After 14, 54, and 60 days of recovery, the generic δ_v values of q_t data are 0.73, 1.11, and 1.01 m, respectively. A slight decrease of the generic δ_v is observed immediately after the compaction, whereas it increases later. This observation indicates that the resonance compaction should make influence on the autocorrelation structure of the soil data. Hence, the variation of the spatial variability of the q_t data could reflect the impact of the compaction. This conclusion will be further demonstrated using the specific analysis.

Figure 6 presents four representative examples of curve fitting of ACMs to ACFs. To evaluate the performance of fitted ACMs to the ACFs, the coefficients of determination (R^2) are also calculated and presented in Figure 6. Basic statistics including the insertion of Bartlett's limit, numbers of the autocorrelation coefficients in both ACFs and curve fitting for ACMs are also shown in Figure 6.

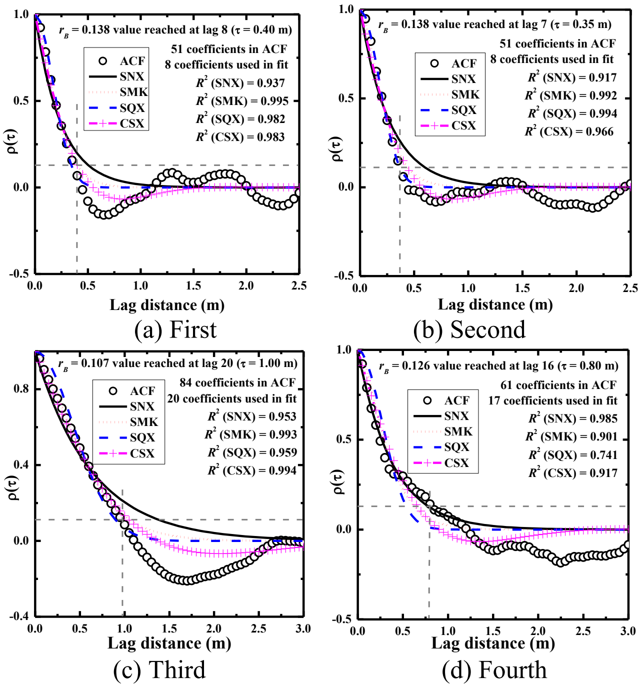


Figure 6. Representative example of best-fit case in: (a) First; (b) Second; (c) Third; (d) Fourth dataset

Figure 7 presents the estimated vertical scales of fluctuation (δ_v) and mean values of q_t records of the middle silt in the four datasets in the specific analysis. Variations of the mean q_t values are quite significant. Before compaction (first dataset), the mean q_t of the middle silt varies from 2 to 7.6 MPa. After 14 days of recovery (second dataset), the mean q_t decreases to the range of 1.5 to 4.8 MPa. However, after 54 and 60 days of recovery, it increases to the range of 7.7 to 12.4 MPa. This observation illustrates that a preliminary reduction of the density of the middle silt occurred immediately after the compaction, whereas the density will increase remarkably during the recovery. Besides, it can be also observed that the mean q_t of the third dataset is slightly higher than that of the fourth dataset, although the recovery age of the former is shorter. This feature shows that the performance of the compaction is more effective at the center of the triangle of three adjacent compaction points, compared to that at the compaction points

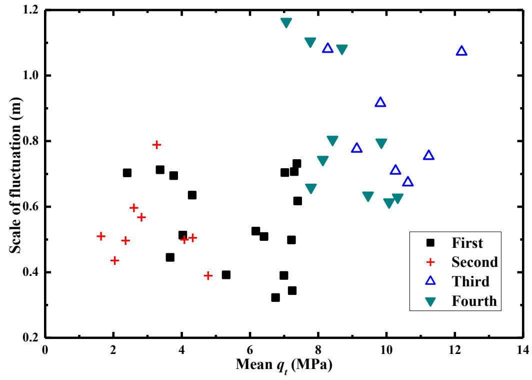


Figure 7. Vertical scales of fluctuation against mean values of q_t record using specific analysis.

The behavior of specific δ_v is similar to that of mean q_t. On the whole, all the specific δ_v values vary from 0.3 to 1.2 m and are consistently in the same magnitude for all the four datasets. Hover, variations of the specific δ_v values of different datasets can be also observed. The specific δ_v values of q_t data before compaction vary widely from 0.3 to 0.8 m with the mean value of 0.55 m. After 14 days of recovery, the specific δ_v values seem to remain the same as those of silt before compaction. However, as the density further grows, the specific δ_v values tend to increase slightly to the range of 0.6 to 1.2 m after 54 and 60 days of recovery. A preliminary decrease and the subsequent increase are observed on the specific δ_v of the q_t data.

The variation of either generic or specific δ_v values could be potentially explained by the mechanism of the penetration test and resonance compaction. The q_t measurements are viewed as the mechanical response of CPTU probe to the surrounding soils. The size of influence zone induced by the penetration of the cone probe increases with the stiffness and strength of the surrounding soils, whereas the vertical scale of fluctuation representing the autocorrelation strength of the soil data should be correlated to the size of the influence zone. During the resonance compaction, the insertion and vibration of the compaction probe destroyed the geotechnical formation of the undisturbed silt. Hence, a preliminary reduction of the strength and stiffness of the subsoil and furthermore the size of the CPTU influence zone can be expected. However, with the recovery of the soil strength, the size of the CPTU influence zone will increase gradually. Therefore, both the mean value and δ_v of the q_t data should decrease immediately after compaction, but these two parameters will gradually increase with the recovery age.

4.2 *Interpretation of coefficients of variation*

The COV quantifies the magnitude of variability of a soil property. Using Equation (2), the COV of q_t can be determined for each record. Figure 8 presents the COVs of q_t for the four datasets using specific analysis. It can be seen clearly that the COVs of q_t decrease with the mean values. Before compaction the COVs of q_t vary from 25 to 45%. This range of COV still remains after 14 days of recovery. However, after 54 and 60 days of recovery, the COV values reduced to 15 to 30%. It is concluded that the resonance compaction technique effectively reduces the uncertainties of q_t of the middle silt.

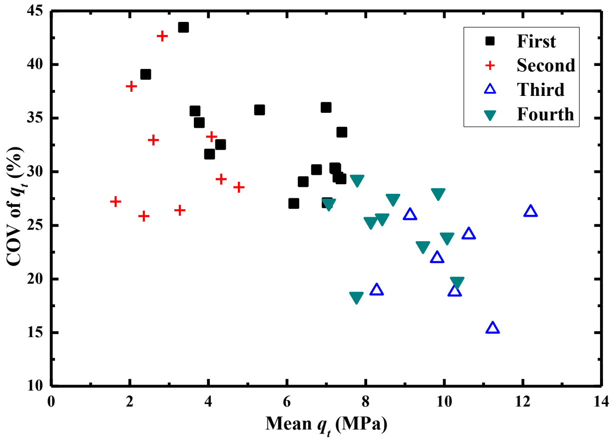


Figure 8. Vertical coefficient of variation against mean values of q_t record using specific analysis.

5 CONCLUSIONS

A novel resonance compaction technique was applied for improving the liquefaction resistance of silts located at the Suqian, China. To evaluate the performance of the compaction, piezocone penetration tests (CPTU) were performed both before and after the improvement. The random field theory was utilized to describe the variation of the spatial variability of q_t data due to the compaction. Three random field model parameters, including mean value, vertical scale of fluctuation (δ_v) and coefficient of variation (COV) of q_t, were analyzed and compared. Results showed that both the mean value and the δ_v decreased immediately after the compaction, but these two parameters gradually increased with the strength and density recovery, whereas the COV consistently decreased after the compaction. This observation could be potentially related to the mechanism of the cone penetration and the resonance compaction. The spatial variability analysis on q_t of the silt demonstrated the effectiveness of the resonance compaction technique in improving the mean strength and density of the silt and simultaneously reducing its uncertainties.

6 ACKNOWLEDGMENTS

Majority of the work presented in this paper was funded by the Foundation for the New Century Excellent Talents of China (NCET-13-0118), the Foundation of Jiangsu Province Outstanding Youth (Grant No. BK20140027), the Foundation for the Author of National Excellent Doctoral Dissertation of PR China (Grant No. 201353), and the High Level Talent Project of Peak of Six Talents in Jiangsu Province (Grant No. 2015-ZBZZ-001). These financial supports are gratefully acknowledged.

7 REFERENCES

Baecher, G. B. & Christian, J. T. 2003. *Reliability and statistics in geotechnical engineering*. John Wiley and Sons, New York.

Cai, G.Y., Liu, S.Y., Puppala, A.J. & Tong, L.Y. 2011. Assessment of the coefficient of lateral earth pressure at rest (Ko) from in situ seismic tests. *Geotechnical Testing Journal*, Vol. 34, No. 4, pp. 310-320.

Cai, G.J., Liu, S.Y. & Puppala, A.J. 2012. Liquefaction assessments using seismic piezocone penetration (SCPTU) test investigations in Tangshan region in China. *Soil Dynamics and Earthquake Engineering*, Vol. 41, pp. 141-150.

DeGroot, D.J. & Baecher, G.B. 1993. Estimating autocovariance of in-situ soil properties. *Journal of Geotechnical Engineering*, ASCE, Vol. 119, No. 1, pp. 147-166.

Jaksa, M.B., Kaggwa, W.S. & Brooker, P.I. 2000. Experimental evaluation of the scale of fluctuation of a stiff clay. *Proceedings of the 8th International Conference on Applications of Statistics and Probability in Soil and Structural Engineering*, Balkema, Rotterdam, pp. 415-422.

Ku, C.S. & Juang, C.H. 2011. Variation of CPTU parameters and liquefaction potential at a reclaimed land induced by dynamic compaction. *Journal of GeoEngineering*, Vol. 6, No. 2, pp. 89-98.

Lunne, T., Robertson, P.K. & Powell, J.J.M. 1997. *Cone penetration testing in geotechnical practice*. Blackie Academic and Professional, London.

Massarsch, K.R. & Fellenius, B.H. 2002. Vibratory compaction of coarse-grained soils. *Canadian Geotechnical Journal*, Vol. 39. No. 3, pp. 695-709.

Massarsch, K.R. & Fellenius, B.H. 2005. Deep vibratory compaction of granular soils. *Chapter 19 in Ground Improvement-Case Histories*, Elsevier publishers, B. Indranatna and C. Jian, Editors, pp. 633 - 658.

Phoon, K.K. & Ching, J. 2012. Beyond coefficient of variation for statistical characterization of geotechnical parameters. *Keynote lecture of Geotechnical and Geophysical Site Characterization 4*, ISC 4, 113-130.

Phoon, K.K., Quek, S.T. & An, P. 2003. Identification of statistically homogeneous soil layers using modified Bartlett statistics. J*ournal of Geotechnical and Geoenvironmental Engineering*, Vol. 129, No. 7, pp. 649–659.

Stuedlein, A.W., Kramer, S.L., Arduino, P. & Holtz, R.D. 2012. Geotechnical characterization and random field modeling of desiccated clay. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 138, No. 11, pp. 1301-1313.

Uzielli, M., Vannucchi, G. & Phoon, K.K. 2005. Random field characterization of stress-normalized cone penetration testing parameters. *Géotechnique*, Vol. 55, No. 1, pp. 3–20.

Vanmarcke, E.H. 2010. *Random fields: Analysis and synthesis.* World Scientific, Singapore.