Paper PO–65

Using Regression Model to Predict Cyclic Resistance Ratio at South Carolina Coastal Plain (SCCP)

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ABSTRACT

Seismically-induced liquefaction is one of the most hazardous geotechnical phenomena from earthquakes that can cause loss of life and devastating damages to infrastructures. In 1964, a 7.5 Richter magnitude earthquake in Nigata, Japan destroyed numerous buildings and structures and initiated studies to understand soil liquefaction. One major outcome of these studies was the development of correlations that are used to determine liquefaction resistance of soil deposits from in-situ soil indices. These relations are based on Holocene soils (<10,000 years old) while the sand deposits encountered in the South Carolina Coastal Plain (SCCP) are older than 100,000 years. In-situ and geotechnical laboratory data that have been obtained in the vicinity of sand blows which date back to 6000 years ago at Fort Dorchester, Sampit, Gapway, Hollywood and Four Hole Swamp sites in the SCCP have been used with methodology that considers the effect of aging on the liquefaction potential of sands to back analyze the cyclic resistance ratio at the time of the prehistoric earthquake. For this paper, descriptive statistics, including frequency distribution for categorical variables and summary statistics for continuous variables, was carried out using this data. Statistical analyses using regression models were performed for selected variables on the calculated values of cyclic resistance ratio (dependent variables). SAS ® 9.4 was used to analyze the data. The main finding is the significant correlation between equivalent clean sand tip resistance and the cyclic resistance ratio at the time of earthquake.

Keywords: SAS, Cyclic Resistance Ratio, Source sand layer.

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INTRODUCTION

The South Carolina Coastal Plain (SCCP) experiences infrequent earthquakes and paleoliquefaction analysis plays an important role in studying the paleoseismicity of this region. Studies performed by Talwani and Schaeffer (2001) show that at least seven, large, prehistoric earthquakes have occurred within the last 6000 years in the SCCP with an average occurrence rate, based on the three most recent events, of about 500 years. Hu et al. (2002a, 2002b) used site-specific geotechnical data (penetration resistance and shear wave velocity) and back analysed the earthquake magnitude (M) and peak ground acceleration (a_{max}) at four sites in the South Carolina Coastal Plain. Back analyses were based on the empirical correlations presented in Youd and Idriss (1997). These relations are based on the studies of recent earthquakes in Japan, China and the west coast region of the U.S. where the soil deposits are of Holocene age (<10,000 years old). Leon et al. (2005) developed a methodology that considered the effect of age in soil deposits and back calculated magnitudes, cyclic resistance ratio (CRR) and peak ground accelerations for the sand deposits in the SCCP that are older than 100,000 years. Neglecting the effect of aging resulted in a 60% underestimation of CRR (Leon et al. 2006).

Gheibi and Gassman (2014) used the Idriss and Boulanger (2008) methodology to back calculate the magnitude, maximum acceleration, and CRR at the Sampit and Gapway sites and showed that using the newer method reduces the acceleration values about 50% for M=5 and 23% for M=7.5 for the Gapway and Sampit sites when compared to using Seed's original method. Similar studies have recently been performed at the Fort Dorchester (Gassman et al., 2015) Hollywood (Gheibi and Gassman, 2015) and Four Hole Swamp sites.

Empirical liquefaction potential assessment correlations are developed based on analyzing experimental studies and case studies. Running statistical analyses on the smaller liquefaction data sets leads to extend meaningful correlations that can be used as a larger data base to predict liquefaction at the sites where complete sets of data are not available. Therefore, the purpose of this paper is to perform regression analysis on the current measurements of field test data (CPT tip resistance values) to predict the cyclic resistance ratio (CRR) of the soil at the time of prehistoric earthquake.

SITE STUDIED

Given the importance of evaluating liquefaction potential in the SCCP, in-situ and geotechnical laboratory tests have performed in the vicinity of sand blows which date back to 6000 years ago at the five sites of Fort Dorchester, Sampit, Gapway, Hollywood and Four Hole Swamp. Cone Penetration Tests (CPT) and Standard Penetration Tests (SPT) were carried out at three to four test locations at each site. Figure 1 indicates the location of these five sites.

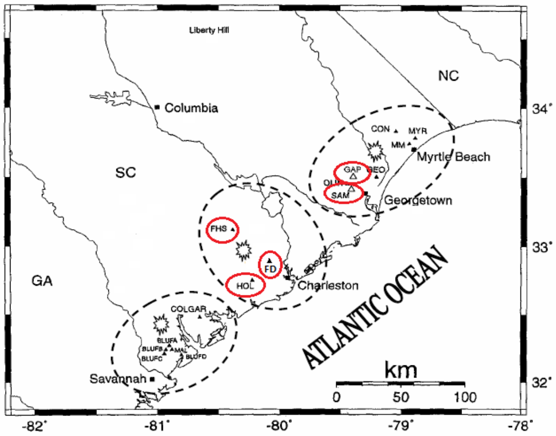

Figure 1. Locations of paleoliquefaction features in South Carolina Coastal Plain

The in-situ data used in this study were obtained from CPT and SPT performed at the site. The geotechnical laboratory tests were also performed on the samples obtained from SPT split spoon sampler to characterize the soil and obtain the fines content. The soil profile was obtained using the field and laboratory test results.

The source sand layer is the layer most prone to liquefaction and was determined using the interpretation of SPT blow counts, CPT tip resistance and laboratory test results. Two scenarios were considered for the depth of source sand layer at Four Hole Swamp. In the first case (A) the source sand layer was assumed to be deeper than the other case (B). In this study, CPT tip resistance data were analysed to calculate the CRR. Table 1. indicates the average value of cone penetration tip resistance in the source sand layer at each test location.

Table 1: Average values of current tip resistance in the source sand layer.

Test Location	q_c (Mpa)
FD-1	5
FD-2	11.2
FD-3	11.3
FD-7	12.8
SAM-1	6.8
SAM-2	6
SAM-3	7.7
GAP-1	3.8
GAP-2	6.6
GAP-3	2.4
HWD-4	6.4
HWD-5	5.5
HWD-6	6.9
FHS-1 (A)	3.6
FHS-2 (A)	6.6
FHS-3 (A)	4.9
FHS-1 (B)	5.7
FHS-2 (B)	9.9
FHS-3 (B)	6.8

Talwani and Schaeffer (2001) found the paleoliquefaction features in freshly cut drainage ditches and described the calibrated ages for the sandblow formations range from 500 to 11,000 years before present and have been associated with liquefaction episodes in SCCP. Ages of sand deposits based on these episodes at all test locations are categorized to four scenarios and are presented in Table 2.

Table 2. Age of sandblows at each test locations (after Talwani and Schaeffer, 2001)

Test Location	t (years before present)			
	First Scenario	Second Scenario	Third Scenario	Forth Scenario
FD-1	3,500	5,000	–	–
FD-2	3,500	5,000	–	–
FD-3	3,500	5,000	–	–
FD-7	3,500	5,000	–	–
SAM-1	1,021	–	–	–
SAM-2	450,000	–	–	–
SAM-3	450,000	–	–	–
GAP-1	5,038	–	–	–
GAP-2	5,038	–	–	–
GAP-3	5,038	–	–	–
HWD-4	546	1,021	3,548	5,038
HWD-5	546	1,021	3,548	5,038
HWD-6	546	1,021	3,548	5,038
FHS-1	1,660	–	–	–
FHS-2	1,660	–	–	–
FHS-3	1,660	–	–	–

METHODOLOGY

The methodology of Leon et al. (2005) was used to obtain the cyclic resistance ratio (CRR) at the time of earthquake. In this method, empirical correlations for liquefaction evaluation which are applicable for young or freshly deposited soils can be used for the older soil deposits if the age corrected parameters (cone penetration tip resistance, q_{c1}, at the time of earthquake) are applied.

Post and pre-earthquake values of tip resistance ($q_{c1\ (post)}$, $q_{c1\ (pre)}$) for the discussed ages and episodes are obtained using two different approaches. Approach 1 is based on the relations offered by Mesri et al. (1990) for both the age and disturbance correction and Approach 2 is based on work by Kulhawy and Mayne (1990) for the age correction and Seed (1988) for the disturbance correction. Change in relative density of the soil (ΔD_R) is considered to be 5% and 10% between the pre- ($q_{c1\ (pre)}$) and post- ($q_{c1\ (post)}$) earthquake state.

Pre-earthquake values of tip resistance at depth of soil are corrected for the effect of fines content in soil using Equation 1 and then are applied in Equation 2 to obtain CRR using the Idriss and Boulanger (2008) approach.

$$(q_{c1N})_{cs} = q_{c1N} + \Delta q_{c1N}\ ,\quad \Delta q_{c1N} = \left(5.4 + \frac{q_{C1N}}{16}\right) * \exp\left\{1.63 + \frac{9.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01}\right)^2\right\} \tag{1}$$

$$CRR_{M=7.5,\sigma'_{vc}=1} = \exp\left\{\frac{(q_{c1N})_{cs}}{540} + \left(\frac{(q_{c1N})_{cs}}{67}\right)^2 - \left(\frac{(q_{c1N})_{cs}}{80}\right)^3 + \left(\frac{(q_{c1N})_{cs}}{114}\right)^4 - 3\right\} \tag{2}$$

Where FC is the percent of fines content in soil, q_{C1N} is the normalized value of tip resistance and $(q_{C1N})_{CS}$ is the equivalent clean sand value of tip resistance.

DATA ANALYSIS

Statistical analyses were used to organize and summarize the data to support the research methodology. Proc MEANS and FREQ were used to describe the data. Proc CORR and REG were used to examine the linear relationship of predicted variables (age of earthquake and fines of content) with outcomes (cyclic resistance ratio at the time of earthquake with two approaches (Approach 1 and 2) and different percentage of change in relative density (5 and 10). Pearson correlation, parameter estimates, and R-Square were used to determine the significant and strength effect among independent variable with outcomes. All data analyses were performed using SAS/STAT ® statistical software, version 9.4 (SAS, 2013).

RESULTS

Table 3a. shows the frequency distribution for the age of earthquake and Table 3b. for the fines content. Fifty percent of obtained soil samples in the SCCP have fines content in the range of 5-12%. The percentage of age of earthquake for each category is between 9% to 15 %. The precision reported herein does not represent the experimental uncertainty.

Table 3. Frequency distribution of a. age and b. fines of content

a. Age of Earthquake				
Age	**Frequency**	**Percent**	**Cumulative Frequency**	**Cumulative Percent**
546	191	8.89	191	8.89
1021	365	16.98	556	25.87
1660	292	13.59	848	39.46
3500	249	11.59	1097	51.05
3548	191	8.89	1288	59.93
5000	249	11.59	1537	71.52
5038	279	12.98	1816	84.50
450000	333	15.50	2149	100.00

b. Fines Content Categories				
Fines Content Categories	**Frequency**	**Percent**	**Cumulative Frequency**	**Cumulative Percent**
0-5	462	21.50	462	21.50
5-12	1077	50.12	1539	71.61
12-35	607	28.25	2146	99.86
Greater than 35	3	0.14	2149	100.00

Table 4 shows the mean, standard deviation, and minimum and maximum of variables. The results show the overall mean of fines content for the obtained soil samples from all the test locations is 9.2. The mean of the current cyclic resistance ratio is 0.17 and is greater than the corresponding values at the time of earthquake for both approaches which is because of the increase in the soil resistance against the liquefaction with time.

Table 4. N, mean, standard deviation, minimum, and maximum for variables.

Variables	N	Mean	Std Dev	Min	Max
Fines content	2149	9.2	4.61	2	38
Equivalent clean sand tip resistance	2149	105	36.5	18	222
Current cyclic resistance ratio	2107	0.17	0.09	0.05	0.57
Cyclic resistance ratio at the time of earthquake, Approach 1, 5%	2149	0.09	0.03	0.05	0.31
Cyclic resistance ratio at the time of earthquake, Approach 1, 10%	2149	0.07	0.01	0.05	0.15
Cyclic resistance ratio at the time of earthquake, Approach 2, 5%	2149	0.12	0.05	0.05	0.51
Cyclic resistance ratio at the time of earthquake, Approach 2, 10%	2149	0.12	0.05	0.05	0.47

Table 5 presents the mean, standard deviation, and minimum and maximum of variables by fines content. Results show that for a given range of fines content, Approach 1 leads to lower values of CRR compared to the Approach 2. The mean of equivalent clean sand tip resistance are 95, 114, 99, 131 for 0-5, 5-12, 12-35, and greater than 35 of fines content levels; respectively. The mean of the cyclic resistance ratio at the time of the earthquake were different with levels of fines of content.

Table5. N, means, standard deviation, minimum, and maximum for variables by fines content levels

Fines Content	Label	N	Mean	Std Dev	Min	Max
0-5	-Equivalent clean sand tip resistance -Current cyclic resistance ratio -Cyclic resistance ratio at the time of earthquake, Approach 1, 5% -Cyclic resistance ratio at the time of earthquake, Approach 1, 10% -Cyclic resistance ratio at the time of earthquake, Approach 2, 5% -Cyclic resistance ratio at the time of earthquake, Approach 2, 10%	462 462 462 462 462 462	95 0.15 0.07 0.06 0.11 0.10	33.77 0.07 0.02 0.01 0.03 0.03	18 0.05 0.05 0.05 0.05 0.05	174 0.45 0.16 0.10 0.22 0.21
5-12	-Equivalent clean sand tip resistance -Current cyclic resistance ratio -Cyclic resistance ratio at the time of earthquake, Approach 1, 5% -Cyclic resistance ratio at the time of earthquake, Approach 1, 10% -Cyclic resistance ratio at the time of earthquake, Approach 2, 5% -Cyclic resistance ratio at the time of earthquake, Approach 2, 10%	1077 1037 1077 1077 1077 1077	114 0.18 0.10 0.07 0.13 0.13	38.18 0.09 0.04 0.02 0.06 0.05	26 0.06 0.05 0.05 0.06 0.06	222 0.57 0.31 0.15 0.51 0.47
12-35	-Equivalent clean sand tip resistance -Current cyclic resistance ratio -Cyclic resistance ratio at the time of earthquake, Approach 1, 5% -Cyclic resistance ratio at the time of earthquake, Approach 1, 10% -Cyclic resistance ratio at the time of earthquake, Approach 2, 5% -Cyclic resistance ratio at the time of earthquake, Approach 2, 10%	607 605 607 607 607 607	99 0.16 0.09 0.07 0.12 0.11	31.73 0.09 0.02 0.01 0.04 0.04	39 0.07 0.06 0.06 0.06 0.06	193 0.56 0.19 0.12 0.29 0.28
Greater than 35	-Equivalent clean sand tip resistance -Current cyclic resistance ratio -Cyclic resistance ratio at the time of earthquake, Approach 1, 5% -Cyclic resistance ratio at the time of earthquake, Approach 1, 10% -Cyclic resistance ratio at the time of earthquake, Approach 2, 5% -Cyclic resistance ratio at the time of earthquake, Approach 2, 10%	3 3 3 3 3 3	131 0.23 0.13 0.10 0.16 0.16	28.52 0.10 0.03 0.01 0.04 0.04	105 0.15 0.11 0.09 0.12 0.12	162 0.34 0.16 0.11 0.21 0.20

Table 6 indicates Pearson correlation among variables. For each variable, three numbers are shown: the first row indicates bivariate correlation, the second row is P-value and the last row shows the number of observations. The results show the positive linear relationship between equivalent clean sand tip resistance and cyclic resistance ratio at the time of earthquake for all cases is greater than 0.75 which is considered to be strong.

Table 7 presents the results from the multiple regression models for equivalent clean sand tip resistance on cyclic resistance ratio at the time of earthquake for Approaches 1 and 2 and different percentages of change in relative density. Each model includes the age of the earthquake and the fines content as predictors. The results indicate there is significant relation between the predictors and outcome variable (CRR at time of earthquake). Parameter estimate in Table 7 is the slope between the predictors and outcome and shows how the CRR at time of earthquake will change by one unit of increase in the predictors. The slopes are different for Approach 1 with different percentages; however, the slopes are similar for Approach 2 with different percentages. 84 % variability of cyclic resistance is explained by equivalent clean sand tip resistance, age of earthquake, and fines content in Approach 1 for both 5 and 10 %. The results also reveal that 91 % variability of cyclic resistance is explained by equivalent clean sand tip resistance, age of earthquake, and fines content with Approach 2 for both 5 and 10 %.

Research is still on going to find the correlation between equivalent clean sand values of tip resistance and the cyclic resistance ratio at the time of earthquake.

Table 6. Pearson Correlation

Pearson Correlation Coefficients Prob > |r| under H0: Rho=0 Number of Observations							
	FC	**qc1Ncs**	**CRRc**	**CRR15**	**CRR110**	**CRR25**	**CRR210**
FC Fines content	1.00000	0.19871 <.0001 2149	0.17426 <.0001 2107	0.43048 <.0001 2149	0.54077 <.0001 2149	0.25273 <.0001 2149	0.24724 <.0001 2149
qc1Ncs Equivalent clean sand tip resistance		1.00000	0.92467 <.0001 2107	0.77656 <.0001 2149	0.74988 <.0001 2149	0.94260 <.0001 2149	0.95095 <.0001 2149
CRRc Current cyclic resistance ratio			1.00000	0.72320 <.0001 2107	0.68974 <.0001 2107	0.96634 <.0001 2107	0.96726 <.0001 2107
CRR15 Cyclic resistance ratio at the time of earthquake, Approach 1, 5%				1.00000	0.98807 <.0001 2149	0.86005 <.0001 2149	0.85102 <.0001 2149
CRR110 Cyclic resistance ratio at the time of earthquake, Approach 1, 10%					1.00000	0.82872 <.0001 2149	0.82067 <.0001 2149
CRR25 Cyclic resistance ratio at the time of earthquake, Approach 2, 5%						1.00000	0.99947 <.0001 2149
CRR210 Cyclic resistance ratio at the time of earthquake, Approach 2, 10%							1.00

Table 7. Multiple regression models for equivalent clean sand tip resistance on cyclic resistance ratio at the time of earthquake for Approach 1 and 2 and different percentages of change in relative density.

Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**	**Standardized Estimate**	**Squared Semi-partial Corr Type II**	**Squared Partial Corr Type II**
Intercept	1	0.02405	0.00101	23.87	<.0001	0	.	.
Age of earthquake	1	-8.88454E-8	1.943581E-9	-45.71	<.0001	-0.45038	0.15669	0.49346
Fines content	1	0.00047404	0.00006966	6.80	<.0001	0.06840	0.00347	0.02113
Equivalent clean sand tip resistance	1	0.00066376	0.00000777	85.39	<.0001	0.75785	0.54672	0.77267

R^2 = .84 Approach 1, 5%

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Standardized Estimate	Squared Semi-partial Corr Type II	Squared Partial Corr Type II
Intercept	1	0.03582	0.00046647	76.79	<.0001	0	.	.
Age of earthquake	1	-3.59756E-8	8.99826E-10	-39.98	<.0001	-0.39193	0.11866	0.42700
Fines content	1	0.00070031	0.00003225	21.71	<.0001	0.21718	0.03500	0.18021
Equivalent clean sand tip resistance	1	0.00028620	0.00000360	79.52	<.0001	0.70227	0.46946	0.74672

R^2 = .84 Approach 1, 10 %

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Standardized Estimate	Squared Semi-partial Corr Type II	Squared Partial Corr Type II
Intercept	1	-0.01151	0.00123	-9.33	<.0001	0	.	.
Age of earthquake	1	-1.99549E-8	2.377846E-9	-8.39	<.0001	-0.06637	0.00340	0.03179
Fines content	1	0.00037841	0.00008523	4.44	<.0001	0.03583	0.00095264	0.00911
Equivalent clean sand tip resistance	1	0.00125	0.00000951	131.19	<.0001	0.93472	0.83168	0.88918

R^2 = .90 Approach 2, 5 %

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Standardized Estimate	Squared Semi-partial Corr Type II	Squared Partial Corr Type II
Intercept	1	-0.00884	0.00109	-8.10	<.0001	0	.	.
Age of earthquake	1	-1.3358E-8	2.107121E-9	-6.34	<.0001	-0.04684	0.00169	0.01839
Fines content	1	0.00037957	0.00007552	5.03	<.0001	0.03789	0.00107	0.01164
Equivalent clean sand tip resistance	1	0.00119	0.00000843	141.66	<.0001	0.94289	0.84628	0.90343

R^2 = .91 Approach 2, 10 %

CONCLUSIONS

PROC REG in SAS was used to examine the relationship between equivalent clean sand tip resistance and cyclic resistance ratio at the time of earthquake with two approaches and two percentages of change in relative density. Each model included the age of the earthquake and the fines content. The results showed the bivariate correlations between equivalent clean sand tip resistance and cyclic resistance ratio at the time of earthquake using Approach 1 for 5 and 10% were 0.78 and 0.75, respectively. Bivariate correlations for Approach 2 were 0.94 and 0.95 for 5 and 10% of change in relative density. The results also revealed that an increase in predictor variable values (fines content, age of earthquake and equivalent clean sand tip resistance) produced different changes in CRR at the time of the earthquake for both 5 and 10% in Approach 1; whereas similar changes were produced for CRR for 5 and 10% in Approach 2. Variability of cyclic resistance ratio were explained 84% and 91% by equivalent clean sand tip resistance, age of earthquake, and fines content in Approaches 1 and 2, respectively.

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TRADEMARK NOTICE

SAS SYNTAX

```
proc format;
value fcgf 1=" 0-5"
              2=" 5-12"
              3="12-35"
              4="greater than 35";
data one;
set  crr.crr14;

if 0<fc =<5 then fcg=1;
else if 5<fc =<12 then fcg=2;
else if 12<fc =<35 then fcg=3;
else if 35<fc<100 then fcg=4;

lABEL
site =" Site"
age = " age of earthquake"
FC  =" fines content"
FCg  =" fines content categories"
qc1ncs  =" equivalent clean sand tip resistance"
CRRc ="current cyclic resistance ratio"
CRR15 ="cyclic resistance ratio at the time of earthquake, method 1, 5%"
CRR110 ="cyclic resistance ratio at the time of earthquake, method 1, 10%"
CRR25 ="cyclic resistance ratio at the time of earthquake, method 2, 5%"
CRR210 ="cyclic resistance ratio at the time of earthquake, method 2, 10%"
;
format fcg fcgf.;
run;

ods rtf;
ods listing close;
proc freq data =ONE;
tables site age fcg;
title ' Frequency tables/';
run;

proc means data=one maxdec=2;
     var fc -- crr210;
     TITLE1 'Mean';
run;
proc means data=one maxdec=2;
    class fcg;
     var qc1ncs -- crr210;
     TITLE1 'Mean';
      run;
proc CORR Data=one ;
     var fc -- crr210;
     TITLE1 'CORREALTION';
run;
ods rtf close;
ods listing;
quit;
run;
ods rtf;
ods listing close;

%macro reg  (d,i,t);
proc reg data=one;
      model &d = &i / stb pcorr2 scorr2;
title ' Regression model' &t;
   %mend reg;
 %reg (crr15,age fc qc1ncs, cyclic resistance ratio at the time of earthquake method 1
5% );
```

```
%reg (crr110,age fc qc1ncs, cyclic resistance ratio at the time of earthquake method 1
10% );
%reg (crr25,age fc qc1ncs, cyclic resistance ratio at the time of earthquake method 2
5% );
%reg (crr210,age fc qc1ncs, cyclic resistance ratio at the time of earthquake method 2
10% );
run;
ods rtf close;
ods listing;
quit;
run;
```