Evaluation of some soil characteristics from field SPT values using random number generation technique

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Abstract. Several engineering attributes, such as soil strength and deformability, are very significant and are regarded as the basis of any sort of foundation design. In determining the vibration extent depending on the used soil numerical models, soil characteristics represented by the shear wave velocity, cohesion, angle of internal friction and Poisson’s ratio are crucial. Different kinds of parameters are identified in various used manuals in numerical modelling. The outputs of these numerical programs are commonly dependent on the input parameters. Thus, in the analysis of any geotechnical problem, the correct selection of rigorous values of the engineering properties of the soil is extremely serious. In this study, a set of field data for Standard Penetration Test (SPT) values has been collected from more than twenty different places in Kirkuk city. In addition, using the random number generation method, several empirical relationships of various soil properties have been advanced in terms of the spectrum of the collected SPT values. The functional benefit of the relationships developed can be used to validate the observed experimental geotechnical data integrated in the architecture of the different civil engineering ventures. As a result, for the SPT-N values ranged from 4 to 44, the predicted soil cohesion and angle of internal of friction increased from 17 kPa to 281 kPa and 4° to 38° respectively. As an overall evaluation, the shear wave velocity ranged from 72 (m/s) to 367 (m/s) whereas the field and predicted UCS varied from 60 kPa to 320 kPa and 54 kPa to 400 kPa respectively.

Keywords. Soil characteristics, SPT, Random generation technique.

1. Introduction

In general, various soil properties have been calculated using field and laboratory experiments, such as elastic and strength characteristics. There is an ability to discard conducting certain experiments in the absence of an appropriate budget, time constraints and a challenging field scenario. Instead, using data from adjoining sites or some statistical correlations are used to assess such soil properties. In the past, empirical correlations have been comprehensively used to estimate the soil properties for published data from various sources including the discrepancy of the test methods, test materials, and data explanation. The empirical soil correlations were established using field Standard Penetration Test values (SPT) N-value. The N-value for its simplicity is commonly used as a simple strength assessment index value. In addition, for calculating soil bearing capacity and shear wave velocity, the N-value is used. The most traditional procedure for general soil characterization is the SPT field test. In terms of N-value, multiple soil correlations are provided in the literature, with no specific reason for considering these correlations. Obtaining a consistent soil correlation can be used in assisting the field engineers when the laboratory and in situ test results are unavailable where it can be beneficial in predicting the mechanical properties of the soil. Different experiments on scientific correlations have been undertaken on distinctive soil types in the past. Empirical correlations were formed between each of the internal friction angles and cohesion with the N-values [1-2]. In addition, correlations between undrained shear strength and N-values were obtained [3-5]. In the recent times, various correlations were attained between shear wave velocity and N-values [6-10]. In terms of degree of saturation, unit weight and modulus of elasticity, traditional analytical models for distinctive blast generated parameters have been developed in the soil [11]. Such data have been analyzed by Raheem and Vipulanandan [12]. Correlations between uniaxial
compressive and traditional strengths for rock mass have been established by Raheem and Vipulanandan [13]. The established relations are relevant for particular soil types compared to the soils evaluated in the literature. Nevertheless, with a large variety of soils, it is impossible to obtain relationships.

The main objective of this paper is to obtain accurate relationships for meaningful soil characteristics depending on various standard penetration data collected from different places in Kirkuk city. Basically, the random generation technique has been used to create several crucial engineering relationships between N-values and different soil properties such as shear wave velocity, angle of internal friction, cohesion, Poisson’s ratio, and unconfined compression strength. Moreover, the obtained relationships have been validated against experimental data.

2. Materials and methods
A set of data from different places of Kirkuk city has been collected and summarized in Table 1. The data includes the location, project type, borehole number and depth, SPT values (average), unconfined compressive strength, and allowable bearing capacity. From Table 1, it can be inferred that all the data obtained from school works with a maximum of three boreholes per project. The maximum borehole depth was 8 m, with a reported maximum N value of 44. The maximum unconfined compressive strength was 380 kPa with a maximum allowable bearing capacity of 105 kPa.

| No. | Location       | Project Type | Borehole No | Depth (m) | SPT (Average) | UCS (kPa) | Remarks                                      |
|-----|----------------|--------------|-------------|-----------|---------------|-----------|---------------------------------------------|
|     |                |              | To          | From      |               |           |                                             |
| 1   | Al Shirqat     | School       | 1           | 0         | 2             | 4         | Recommended allowable bearing capacity is 60 kPa. |
|     |                |              | 1           | 4         | 6             | 10        |                                             |
|     |                |              | 1           | 6         | 8             | 17        |                                             |
|     |                |              | 2           | 0         | 2             | 5         |                                             |
|     |                |              | 2           | 4         | 6             | 9         |                                             |
|     |                |              | 2           | 6         | 8             | 18        |                                             |
|     |                |              | 3           | 0         | 2             | 5         |                                             |
|     |                |              | 3           | 4         | 6             | 10        |                                             |
|     |                |              | 3           | 6         | 8             | 17        |                                             |
| 2   | Al Multaqa     | School       | 1           | 0         | 2             | 8         | Recommended allowable bearing capacity is 70 kPa. |
|     |                |              | 1           | 4         | 6             | 19        | 120                                         |
|     |                |              | 1           | 6         | 8             | 34        | 200                                         |
|     |                |              | 2           | 0         | 2             | 7         | 70                                          |
|     |                |              | 2           | 4         | 6             | 18        | 110                                         |
|     |                |              | 2           | 6         | 8             | 32        | 190                                         |
| 3   | Al-Qadisiyah   | School       | 1           | 0         | 2             | 6         | Recommended allowable bearing capacity is 75 kPa. |
|     |                |              | 1           | 4         | 6             | 13        | 100                                         |
|     |                |              | 1           | 6         | 8             | 25        | 160                                         |
|     |                |              | 2           | 0         | 2             | 7         | 70                                          |
|     |                |              | 2           | 4         | 6             | 15        | 110                                         |
|     |                |              | 2           | 6         | 8             | 25        | 200                                         |
| 4   | Arafa          | Kindergarten | 1           | 0         | 4             | 21        | Recommended allowable bearing capacity is 80 kPa. |
|     |                |              | 1           | 4         | 8             | 33        |                                             |
|     |                |              | 2           | 0         | 4             | 18        |                                             |
|     |                |              | 2           | 4         | 8             | 33        |                                             |

Table 1. Collected data from different locations in Kirkuk city. (continue)
| No. | Location        | Project Type | Borehole No. | Depth (m) | SPT (Average) | UCS (kPa) | Remarks                                |
|-----|-----------------|--------------|--------------|-----------|---------------|-----------|----------------------------------------|
| 5   | Raheem Awa | School      | 1   | 0-2       | 7            | 80        | Recommended allowable bearing capacity is 80 kPa. |
|     |                |              | 1   | 1-4       | 16           | 100       |                                        |
|     |                |              | 1   | 1-6       | 26           | 210       |                                        |
|     |                |              | 2   | 0-2       | 8            | 90        |                                        |
|     |                |              | 2   | 2-4       | 14           | 120       |                                        |
|     |                |              | 2   | 2-6       | 15           | 120       |                                        |
| 6   | Imam Qasim | School      | 1   | 0-2       | 7            | 80        | Recommended allowable bearing capacity is 80 kPa. |
|     |                |              | 1   | 1-4       | 16           | 100       |                                        |
|     |                |              | 1   | 1-6       | 28           | 210       |                                        |
|     |                |              | 2   | 0-2       | 7            | 90        |                                        |
|     |                |              | 2   | 2-4       | 15           | 120       |                                        |
|     |                |              | 2   | 2-6       | 27           | 200       |                                        |
| 7   | Daquq        | School      | 1   | 0-4       | 13           | 100       | Recommended allowable bearing capacity is 90 kPa. |
|     |                |              | 1   | 1-4       | 26           | 200       |                                        |
|     |                |              | 2   | 0-4       | 13           | 90        |                                        |
|     |                |              | 2   | 2-4       | 26           | 210       |                                        |
|     |                |              | 3   | 0-4       | 17           | 80        |                                        |
|     |                |              | 3   | 4-8       | 30           | 190       |                                        |
| 8   | Daquq        | School      | 1   | 0-4       | 13           | 100       | Recommended allowable bearing capacity is 90 kPa. |
|     |                |              | 1   | 1-4       | 26           | 200       |                                        |
|     |                |              | 2   | 0-4       | 13           | 90        |                                        |
|     |                |              | 2   | 2-4       | 26           | 210       |                                        |
|     |                |              | 3   | 0-4       | 17           | 80        |                                        |
|     |                |              | 3   | 4-8       | 30           | 190       |                                        |
| 9   | Hay Al Thawra | School     | 1   | 0-2       | 10           | 110       | Recommended allowable bearing capacity is 90 kPa. |
|     |                |              | 1   | 1-4       | 23           | 130       |                                        |
|     |                |              | 1   | 1-6       | 38           | 300       |                                        |
|     |                |              | 2   | 0-2       | 9            | 90        |                                        |
|     |                |              | 2   | 4-6       | 22           | 120       |                                        |
|     |                |              | 2   | 6-8       | 35           | 140       |                                        |
| 10  | Al-Khan village, Hawija | School | 1   | 0-4       | 14           | 100       | Recommended allowable bearing capacity is 100 kPa. |
|     |                |              | 1   | 1-4       | 25           | 180       |                                        |
|     |                |              | 2   | 0-4       | 12           | 110       |                                        |
|     |                |              | 2   | 4-8       | 22           | 190       |                                        |
| 11  | Daquq | School      | 1   | 0-2       | 14           | 100       | Recommended allowable bearing capacity is 100 kPa. |
|     |                |              | 1   | 1-4       | 26           | 200       |                                        |
|     |                |              | 1   | 1-6       | 36           | 300       |                                        |
|     |                |              | 2   | 0-2       | 13           | 120       |                                        |
|     |                |              | 2   | 4-6       | 24           | 240       |                                        |
|     |                |              | 2   | 6-8       | 38           | 360       |                                        |

*Table 1.* Collected data from different locations in Kirkuk city. (continue)
### Soil Parameters Required for Numerical Modelling

The necessary soil parameters for numerical modelling are unit weight ($\gamma$), Poisson’s ratio ($\mu$), Young’s modulus ($E$), cohesion ($C$), seismic velocity ($v_p$), tensile strength and angle of internal friction ($\phi$). Moreover, the essential parameters for rock modelling are unit weight ($\gamma$), UCS ($f_c$), Poisson’s ratio ($\mu$), Young’s modulus ($E$), tensile strength, angle of internal friction ($\phi$), cohesion ($C$), and seismic velocity ($v_p$). As these soil characteristics are assessed, other parameters are calculated using mathematical relationships. The SPT-N values are measured using field simple test and it can be obtained during the process of soil exploration. The SPT test is a very reasonable low-cost test. The random number generation technique can be utilized to develop empirical relationships between various soil parameters and SPT-N values. The generated relationships are correlating the cohesion, Poisson’s ratio, angle of internal friction, and shear wave velocity with SPT-N values. As these models are advanced, aforementioned most usual soil input parameters can be calculated.

### Random Number Generation Technique

In the present study, random variables have been developed including shear wave velocity, angle of internal friction, cohesion, SPT-N values and Poisson’s ratio where such variables have been represented depending on their probabilistic features. When adequate knowledge in the literature is unobtainable, the random number generation approach is used. Latin Hypercube Sampling method (LHS) is implemented as a reasonable approach compared to the laboratory soil testing [14]. Both Upper and
lower bounds of these random data are known, and a uniform distribution is used in the absence of the mean and standard deviation.

5. Results

5.1. Correlation between cohesion and SPT-N values

Karol (1960) [15] has proposed a correlation between the soil cohesion and SPT-N values based on the soil conditions that vary from very soft to hard conditions corresponding to SPT-N and cohesion values as summarized in Tables 2 and 3 respectively.

| Soil Conditions | Hard | Very Stiff | Stiff | Firm | Soft | Very Soft |
|-----------------|------|------------|-------|------|------|-----------|
| Cohesion (kPa)  | 192  | 96-192     | 48-96 | 24-48| 12-24| 12        |
| SPT-N Values    | >30  | 15-30      | 8-15  | 4-8  | 2-4  | <2        |

Table 3. Various soil cohesion and SPT-N values for intermediate soils [15].

| Soil Conditions | Dense | Medium | Loose |
|-----------------|-------|--------|-------|
| Cohesion (kPa)  | 48    | 5-48   | 5     |
| SPT-N Values    | >30   | 10-30  | <10   |

It can be noticed from both Tables 2 and 3 that SPT-N values range from 2 to 30 and the cohesion varies from 5 kPa to 192 kPa with different soil conditions. Based on the used random number generation technique, around 300 data point has been created to simulate the relation between the cohesion versus the SPT-N values. A correlation has been built between the random generated values of soil cohesion with their corresponding SPT-N values as follows:

\[ C (kPa) = 6.5808 \times N - 9.079 \quad (R^2 = 0.9942) \]  

(1)

Where: C is the cohesion (kPa), and N is SPT-values.

The random distribution of cohesion with the SPT-N values has been shown in Figure 1.

\[ C = 6.5808 \times N - 9.079 \]

\[ R^2 = 0.9942 \]

Figure 1. The random distribution of soil cohesion with SPT-N values.

5.2. Correlation between angle of internal friction and SPT-N values
Terzaghi and Peck (1967) [16] have given a wide range of soil angle of internal friction with SPT-N values for various soil conditions as summarized in Table 4.

| Soil Conditions | Very Good | Good | Fair | Poor | Very Poor |
|-----------------|-----------|------|------|------|-----------|
| Angle of Internal Friction (°) | >41 | 36-41 | 30-36 | 28-30 | <28 |
| SPT-N Values | >50 | 30-50 | 10-30 | 4-10 | 0-4 |

It can be noticed from Table 4 that SPT-N values range from 0 to 50 and the angle of internal friction varies from 0° to 41° with different soil conditions. Based on the used random number generation technique, around 300 data points has been created to simulate the relation between the angles of internal friction versus the SPT-N values. A correlation has been developed between the random generated values of soil angle of internal friction with their corresponding SPT-N values as follows:

\[
\phi (°) = 0.8531 \times N + 0.1581 \quad (R^2 = 0.9963)
\]  

(2)

Where: \(\phi\ (°)\) is the angle of internal friction, and \(N\) is SPT-values.

The random distribution of angles of internal friction with the SPT-N values has been shown in Figure 2.

![Fig. 2. The random distribution of soil angles of internal friction with SPT-N values.](image)

5.3. Correlation between shear wave velocity and SPT-N values

For a broad variety of data obtained from the literature, the variation of shear wave velocity with SPT-N values is summarized in Table 5 [16-19].

| Soil Type        | Loose Granular Soil | Dense Granular Soil | Soft Clay | Stiff Clay |
|------------------|---------------------|---------------------|-----------|------------|
| Shear Wave       | 130-280             | 200-410             | 40-90     | 65-140     |
| Velocity (m/s)   |                     |                     |           |            |
| SPT-N Values     | 0-20                | 20-50               | 0-6       | 6-30       |
| Poisson’s Ratio, \(\mu\) | 0.2-0.4           | 0.3-0.45           | 0.15-0.25 | 0.2-0.5    |
It can be noticed from Table 5 that there are four distinct types of soils with different shear wave velocity. As the data is not continuous in various ranges, for each type of soil, three hundred data points have been generated. Four correlations have been developed between the random generated values of soil shear wave velocity with their corresponding SPT-N values for different soil types as follows:

\[
V\left(\frac{m}{s}\right) = 7.0184 \times N + 125.45 \quad (R^2 = 0.9852) \quad for \text{ loose granular soil} \\
V\left(\frac{m}{s}\right) = 6.7298 \times N + 70.566 \quad (R^2 = 0.9973) \quad for \text{ dense granular soil} \\
V\left(\frac{m}{s}\right) = 7.5743 \times N + 42.011 \quad (R^2 = 0.9794) \quad for \text{ soft clay soil} \\
V\left(\frac{m}{s}\right) = 2.8538 \times N + 55.769 \quad (R^2 = 0.9879) \quad for \text{ stiff clay soil}
\]

Where: \(V\) (m/s) is the shear wave velocity, and \(N\) is SPT-values.

The data for each type of soil has been drawn as shown in Figure 3 (a to d) for loose granular soil, dense granular soil, soft clay and stiff clay respectively.

![Figure 3](image)

**Figure 3:** The random distribution of shear wave velocity with SPT-N values for (a) loose granular soil, (b) dense granular soil, (c) soft clay soil, and (d) stiff clay soil.

### 5.4. Correlation between Poisson’s ratio and SPT-N values

Various soils with different ranges of Poisson’s ratio and SPT-N values have been reported in the literature [20] as summarized in Table 4. Since the data is discrete in several ranges, for each range, three hundred data points have been produced. Four correlations have been advanced between the random generated values of soil Poisson’s ratio with their corresponding SPT-N values for different soil types as follows:

\[
\mu = 0.0195 \times N + 0.0093 \quad (R^2 = 0.9935) \quad for \text{ loose granular soil} \\
\mu = 0.0138 \times N - 0.2721 \quad (R^2 = 0.9933) \quad for \text{ dense granular soil} \\
\mu = 0.0352 \times N + 0.0175 \quad (R^2 = 0.9782) \quad for \text{ soft clay soil} \\
\mu = 0.0207 \times N - 0.1078 \quad (R^2 = 0.9889) \quad for \text{ stiff clay soil}
\]
Where: $\mu$ is the Poisson’s ratio, and $N$ is SPT-values.

The data for each type of soil has been drawn as shown in Figure 4 (a to d) for loose granular soil, dense granular soil, soft clay and stiff clay respectively.

Fig. 4. The random distribution of soil Poisson’s ratio with SPT-$N$ values for (a) loose granular soil., (b) dense granular soil, (c) soft clay soil, and (d) stiff clay soil.

5.5. Correlation between UCS and SPT-$N$ values

For a wide range of data obtained from the literature, the variation of unconfined compressive strength (UCS) with SPT-$N$ values is summarized in Table 6 [17, 21].

Table 6. Various soil types with corresponding SPT-$N$ values, and unconfined compressive strength [17, 21].

| Soil Type         | Very Soft | Soft | Medium | Stiff | Very Stiff | Hard  |
|-------------------|-----------|------|--------|-------|------------|-------|
| Soil Consistency  | 0-25      | 25-50| 50-100 | 100-200 | 200-400    | >400  |
| Unconfined Compressive Strength (kPa) |            |      |        |       |            |       |
| SPT-$N$ Values    | 0-2       | 2-4  | 4-8    | 8-16  | 16-32      | >32   |

It can be noticed from Table 6 that there are six different types of soils with different unconfined compressive strength. As the data is not continuous in these ranges, for each type of soil, three hundred data points have been created. Six correlations have been advanced between the random generated values of soil unconfined compressive strength with their corresponding SPT-$N$ values for different soil types as follows:

- $UCS(kPa) = 8.3991 \times N + 3.4763 \quad (R^2 = 0.8769)$ for very soft soil
- $UCS(kPa) = 8.5346 \times N + 12.394 \quad (R^2 = 0.8875)$ for soft soil
- $UCS(kPa) = 10.78 \times N + 9.5755 \quad (R^2 = 0.9536)$ for medium soil
- $UCS(kPa) = 11.362 \times N + 15.028 \quad (R^2 = 0.9843)$ for stiff soil
- $UCS(kPa) = 11.8 \times N + 19.952 \quad (R^2 = 0.9913)$ for very stiff soil
- $UCS(kPa) = 32.113 \times N - 627.45 \quad (R^2 = 0.9864)$ for hard soil
Where: UCS (kPa) is the unconfined compressive strength, and N is SPT-values.

The data for each type of soil has been illustrated as shown in Figure 5 (a to f) for very soft soil, soft soil, medium soil, stiff soil, very stiff soil, and hard soil respectively.

![Graphs](image)

**Figure 5**: The random distribution of soil USC with SPT-N values for (a) very soft soil, (b) soft soil, (c) medium soil, (d) stiff soil, (e) very stiff soil, and (f) hard soil.

5.6. **Validation of obtained soil correlations with field SPT N values**

The soil cohesion values have been predicted depending on the SPT-N data for Kirkuk city using Eq. 1 as shown in Fig 6. For the SPT-N values ranged from 4 to 44, the predicted soil cohesion increased from 17 (kPa) to 281 (kPa). It is clearly indicated that the places with low cohesion are mainly granular soil whereas the places with high cohesion are cohesive soil zones.

In a similar manner, the field SPT values have been used to predict the expected angle of internal friction for Kirkuk soil as shown in Figure 7. For the SPT-N values ranged from 6 to 44, the predicted angle of internal friction increased from 4° to 38°. It is clearly indicated that the places with low angle of internal friction are mainly cohesive soil whereas the places with high angle of internal friction are granular soil zones.
Figure 6: The variation of soil cohesion with SPT-N values for Kirkuk city.

Figure 7: The prediction of soil angle of internal friction for Kirkuk soil using field SPT-N values.

Moreover, the field SPT values have been expanded to estimate the expected Poisson’s ratio for Kirkuk soil as shown in Figure 8. For the SPT-N values ranged from 6 to 44, the predicted Poisson’s ratio varied from 0.01 to 0.49. It is clearly shown that the places with low Poisson’s ratio are mainly soft clay or loose granular soil whereas the places with high Poisson’s ratio are stiff clay or dense granular soil zones.

Figure 8: The prediction of soil Poisson’s ratio for Kirkuk soil using field SPT-N values.
Moreover, the field SPT values have been extended to estimate the expected shear wave velocity for Kirkuk soil as shown in Fig. 9. For the SPT-N values ranged from 0 to 20 with loose granular soil, the predicted shear wave velocity increased from 154 (m/s) to 266 (m/s). For the SPT-N values ranged from 20 to 44 with dense granular soil, the predicted shear wave velocity increased from 205 (m/s) to 367 (m/s). For the SPT-N values ranged from 0 to 6 with soft clay soil, the predicted shear wave velocity increased from 72 (m/s) to 88 (m/s). For the SPT-N values ranged from 6 to 30 with dense granular soil, the predicted shear wave velocity increased from 73 (m/s) to 141 (m/s). As an overall evaluation, the shear wave velocity ranged from 72 (m/s) to 367 (m/s) where the granular soils have a higher shear wave velocity than the cohesive soils.

Furthermore, the field SPT values have been used to compare the expected UCS for Kirkuk soil with the field data for the UCS as shown in Fig. 10. Most of the soil types in Kirkuk city are in the range of medium soil to very stiff soil and the obtained equations have an over prediction for the UCS compared to the field soil. For the field SPT-N values ranged from 6 to 44, the UCS increased from 60 kPa to 340 kPa. However, the predicted UCS varied from 37 kPa to 786 kPa for the same corresponding SPT-N values. For the range of medium to very stiff soils, the field and predicted UCS varied from 60 kPa to 320 kPa and 54 kPa to 400 kPa respectively. Thus, in the range of Kirkuk field soil, the field and predicted UCS are in a very good agreement.

6. Conclusions
SPT is one of the most successful and popular experiments used to estimate the mechanical properties of soil easily and cheaply. Via the random number generation technique, the relations of cohesion, angle of internal friction, shear wave velocity, Poisson’s soil ratio and UCS in terms of SPT N value were developed. For both soil cohesion and angle of internal friction, single relationships were established. For both shear wave velocity and Poisson’s ratio, four distinctive relations have been illustrated. For the UCS, six relations have been created. All the generated relations have been used to estimate the essential
soil characteristics for Kirkuk city depending on various field SPT-N values. Based on the developed relations with the collected SPT-N values, the following conclusions can be drawn:

1- As the SPT-N values varied from 4 to 44, the predicted soil cohesion increased from 17 (kPa) to 281 (kPa).
2- With increasing the SPT-N values from 6 to 44, the predicted angle of internal of friction increased from 4° to 38°.
3- For the SPT-N values ranged from 6 to 44, the predicted Poisson’s ratio varied from 0.01 to 0.49.
4- The shear wave velocity varied from 72 (m / s) to 367 (m / s) as an average assessment, where the granular soils had a higher shear wave velocity than the cohesive soils.
5- For the range of medium to very stiff soils, the field and predicted UCS were in a very good agreement.

References
[1] Hettriarachchi H and Brown T 2009, J Geotech Geo Environ Eng ACSE 135, p830
[2] Raheem A M 2019, International Journal of Engineering and Technology Innovation 9 (1):1
[3] Kalantary F, Ardalan H, and Nariman-Zadeh N 2009, Eng Geol 104, p144
[4] Raheem A M 2018, Petroleum and Coal 66(60):1087
[5] Raheem A M, and Vipulanandan C 2019, Acta Geodenaica et Geomaterialia 16(1):71
[6] Hasanbebi N, and Ulusay R 2007, Bull Eng Geol Environ 66, p203
[7] Anbazhagan P, and Sitharam T G 2010, Geotech Test J 33(2):1
[8] Akin M K, Kramer S L, and Topal T 2011, Eng Geol 119,1
[9] Sun C G, Cho C S, Son M, and Shin J S 2013, Pure appl Geophys 170, p271.
[10] Raheem A M, and Vipulanandan C 2019b, Engineering Science and Technology, an International Journal 22(3):979
[11] Raheem A M 2020, Key Engineering Materials 857, p302.
[12] Raheem A M, and Vipulanandan C 2020a, Journal of Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 42(3):344.
[13] Raheem A M, and Vipulanandan C 2020b, Journal of King Saud University-Engineering Sciences, https://doi.org/10.1016/j.jksues.2020.10.002
[14] Mckay M D, Bechman R J, and Conover W J 1979, Techno metrics 21(2):239
[15] Karol R H 1960, Soils and soil engineering, Prentice Hall, Eaglewood Cliffs
[16] Terzaghi K and Peck R B 1967 Soil mechanics in engineering practice, 2nd Edn. (New York:Wiley)
[17] Peck R B, Hanson W E and Thornburn T H 1974, Foundation engineering, 2nd Edn. (New York:Wiley & Sons Inc).
[18] Matasovic N and Kavazanjian E J 1998, J Geotech Geoenviron Eng ASCE 124(3),197
[19] Vipulanandan C, and Raheem A M 2015, Proceedings of the International Offshore and Polar Engineering Conference, p1048
[20] Das B M 1994, Principles of Geotechnical Engineering, PWS Publishing Company
[21] Bowles J E 1977, Foundation Analysis and Design, 2nd Edn., (New York:McGraw-Hill)