Modified Methods for Relative Density of Deep Covered Sand Based on Standard Penetration Blow Number

Wen-Ming Peng, Yu-Sheng Yang, Bing-Nan Jiang, Yong Xia

1 PowerChina Chengdu Engineering Corporation Limited, Chengdu, 610072, China
2 Geotechnical Engineering Institute of China Institute of Water Resources and Hydropower Research, Beijing, 100038, China
3 School of Civil Engineering, Southwest Jiaotong University, Chengdu, Sichuan 610031, China

Abstract. Relative density is an important index to evaluate the properties of deep covered sand, and also the key to the laboratory sample preparation and simulation test. Relative density can be obtained by in-situ tests such as standard penetration test (SPT). Based on the existing achievements of determining the relative density of sand by SPT, this paper estimates the relative density of deep-covered sand by empirical formulas and empirical parameters, but the result is obviously smaller. So a correction methods are proposed, i.e. method 1st: Use constant $c=a/b$ to transform the empirical formula, reduce the number of constants, and determine the constant $c$ and the grain size coefficient $C_d$ based on the physical properties of the sand. The relative density calculated by method 1st is generally close to the in-situ test results, but there is still a problem of low relative density of deep sand. For this reason, on the basis of method 1st, the overburden pressure correction is also required for the deep-covered sand, namely method 2nd: correcting the effective stress of the deep soil layer based on the critical depth theory. Method 2nd avoid the unreasonable phenomenon that the relative density becomes smaller as the depth of the soil layer is more deeply buried. After comparative analysis, the calculation results of the method in this paper are very close to the in-situ test of boreholes. It solves the problem of the difficulty in sampling deep-covered sandy soil in its original state, and the small number of samples leads to low accuracy of the relative density results.

1. Introduction

Sandy soil is non-cohesive soil, and its compact state is usually expressed by relative density. The relative density of sand is the basic index for sample preparation to determine the physical and mechanical parameters of sand in laboratory tests; is also an index that characterizes the sand filling standard and an index for the evaluation of sand seismic liquefaction.

For deep covered sandy soil, the layered structure of the soil is complex and has a significant in-situ structure effect (e.g., Liu, X. S. 1993, Jiang, S. T. 1991). The traditional drilling-sampling-indoor test method is difficult to obtain the true original sample due to the influence of stress release and sampling disturbance. Therefore, it is also difficult to accurately determine the in-situ relative density of the sand, which affects the accuracy of measuring mechanical parameters of sandy soil. Compared with the drilling-sampling-indoor test, the in-situ test is carried out under the condition of the natural structure, natural gradation, natural water content and in-situ stress of the soil, which can avoid the influence of equipment, methods, personnel and other factors in the sampling process. If in-situ testing and indoor testing are jointly researched, engineering characteristic parameters with higher accuracy can be obtained. For example, the relative density, bearing capacity and liquefaction judgment of sand can be
estimated based on the SPT. However, the SPT is closely related to the sand particle gradation and consolidation characteristics, and the sand burial depth also has a great influence. Therefore, when estimating the physical and mechanical parameters of sand, the blind application of the empirical formula of the SPT may lead to a large error. It is very important to select the empirical formula and calculation parameters according to the occurrence conditions of the sand.

Based on the geological survey of a deep overburden, this paper discusses a modified method of determining the in-situ relative density of sandy soil based on the SPT. The research can provide a basis for the evaluation of the tightness of the sandy soil, the identification of seismic liquefaction and the determination of the control indicators of the indoor test sample preparation.

2. In-situ test results of deep-covered sand

2.1. Basic physical properties of sand

The foundation of a certain project is a deep overburden layer, the upper layer (layer 1st) is modern accumulation (Q$_{4}$al$_{4}$) pebble-bearing gravel layer with a thickness of about 6m-20m, and the lower layer (layer 2nd) is a river-lake facies accumulation layer (Q$_{3}$al+l$$_{3}$) with a thickness of about 150m. Layer 2nd is composed of dark gray to gray black gravel-bearing medium-coarse sand layer with medium-fine sand layer lens, etc. Layer 2nd has a greater impact on the construction of the project, and it is the sand layer that this article focuses on.

According to the physical property test of layer 2nd, the average moisture content is 7.47%; the average dry density is 1.72g/cm$^3$; the average void ratio is 0.57; the average specific gravity is 2.68. The proportions of coarse, medium and fine sand are basically the same. The average content of coarse sand (0.5~2mm) is 24.37%, the average content of medium sand (0.25~0.5mm) is 21.53%, and the average content of fine sand (0.075~0.25mm) is 33.66%. The average particle content of <0.075mm is 10.19%, and the average particle content of <5mm is 94.09%.

2.2. In-situ test results

2.2.1 Drilling in-situ density test. During the survey process, the γ-γ radioactive in-situ density logging method was used to complete 39 in-situ density test in 11 boreholes for layer 2nd. According to the test results of the maximum and minimum dry density in the sampling chamber of the corresponding hole section, the relative density based on the in-situ density is obtained, as shown in Figure 1 (ZKM is the borehole number). It can be seen from the figure that the in-situ relative density of layer 2nd sand is between 0.67-0.91, with an average value of 0.80, and as the depth increases, the relative density distribution range gradually narrows.

Combining the relevant data of the borehole histogram, the in-situ density of the borehole is corresponding to the position of the sand layer, and the relative density of the gravel-bearing medium-coarse sand layer and medium-fine sand layer is sorted out (see Table 1). The analysis shows that the relative density of the sand layer increases as the depth increases; at the same depth, the relative density of the medium-fine sand layer is slightly greater than that of the medium-coarse sand layer.

2.2.2 Drilling standard penetration test. SPT were carried out in 4 boreholes, and the total length of the test holes in layer 2nd is about 284m, and 243 sets of 30cm penetration test results were obtained. Table 2 shows the collation and statistics of the SPT results of each hole segment, and draws the distribution diagram of the blow number of SPT (see Figure 2). From the test data, it can be seen that the blow number of standard penetrations increases with the increase in depth. The distribution range of the number of standard penetrations is 23~79, the overall average is 42, and the maximum buried depth of the test hole segment reaches 96m. As can be seen from Figure 2, the blow number in the range of 25m~35m in depth of ZKm402 is significantly higher and should be eliminated.
Table 1. Relative density statistics table of drilling in-situ test.

| Location   | Sand name                        | $D_r$ average |
|------------|----------------------------------|---------------|
| Shallow (<65m) | Gravel-bearing medium-coarse sand | 0.770         |
|            | Medium-fine sand                 | 0.803         |
| Deep (>65m) | Gravel-bearing medium-coarse sand | 0.813         |
|            | Medium-fine sand                 | 0.840         |

Table 2. Statistical Table of Standard Penetration Test Results.

| Borehole name | Depth (m)  | Test groups | SPT $N_m$ |
|---------------|------------|-------------|-----------|
| ZKm104        | 20.30~91.80| 55          | 27~69(46) |
| ZKm205        | 15.60~89.85| 72          | 23~58(39) |
| ZKm306        | 24.28~86.07| 55          | 23~64(42) |
| ZKm402        | 20.10~96.45| 61          | 26~79(49) |

Note: 27~69 (46) in the table indicate the minimum ~ the maximum value (average value)

Figure 1. Distribution of the in-situ relative density of the borehole.

Figure 2. Distribution diagram of the blow number of SPT.

3. Estimate relative density with normalized empirical formula

3.1. Standard penetration number and effective overburden pressure

Terzaghi and Peck (1948) were the first to associate penetration number with the relative density of sand. The U.S. Bureau of Reclamation (Gibbs & Holtz, 1957) and the Waterway Test Station (Bieganousky & Marcuson, 1976) further proves that the number of standard penetrations is closely related to the relative density $D_r$ and the effective overburden pressure, with indoor full-scale penetration test on sandy soil. Some researchers had also conducted a large number of field penetration tests on sandy soil foundations. For example, Satio (1977) et al. conducted a field penetration test on the fine sand filler layer on Ogishima Island. Ishihara and Koga (1981) performed field penetration tests on the sand foundations of the Kawagishi-cho site and South Bank site during the Niigata earthquake in 1964. Both the indoor and on-site penetration test data show that under a certain overlying effective stress condition, the penetration hammer number $N_m$ increases with the increase of relative density $D_r$; at a certain relative density, the penetration hammer number $N_m$ increases with the increase of effective overburden pressure. According to the sand test results with a relative density of $0.35 < D_r < 0.85$ and an effective overburden pressure of $50kPa < \sigma_{vo} < 250kPa$, Meyerhof (1957) first proposed that the blow number of SPT, the relative density and the effective overburden pressure have the following relationship:

$$\frac{N_m}{D_r^2} = a + b\sigma_{vo} / \rho_a$$ (1)
Where: \(N_m\) — measured number of SPT; \(D_r\) — Relative density expressed as a ratio; \(\sigma_{vo}'\) — the effective overburden pressure in kPa; \(P_a\) — Atmospheric pressure; \(a, b\) — constant number. The effective overburden pressure \(\sigma_{vo}'\) can be calculated by the following formula:

\[
\sigma_{vo}' = \sum \gamma_i \Delta h_i
\]  

(2)

Where \(\gamma_i\) is the effective weight of the overlying soil layer \(i\), and \(\Delta h_i\) is the thickness of the soil layer \(i\). When \(\sigma_{vo}' = P_a\), formula (1) is simplified to

\[
\frac{N_i}{D_r^j} = a + b
\]  

(3)

In order to facilitate practical applications, the measured penetration blow number \(N_m\) under different effective overburden pressure is often normalized to \(N_1\) under effective overburden pressure of 100kPa (that is, one atmosphere), that is

\[
N_i = C_N N_m
\]  

(4)

Where: \(C_N\) — the normalization coefficient of the effective overburden pressure, expressed by the following formula

\[
C_N = \frac{a + b}{a + b \sigma_{vo}' / P_a}
\]  

(5)

3.2. The relationship between \(N_1\) and \(D_r\)

The relationship between \(N_1\) and \(D_r\) can be expressed as

\[
\frac{N_i}{D_r^j} = C_d
\]  

(6)

Where: \(C_d\) — grain size effect coefficient. Comparing formula (3) and formula (6), we can see that \(C_d\) is closely related to \(a\) and \(b\).

The initial study by Meyerhof (1957) showed that \(C_d\) was 41. Skempton (1986) noted that the sedimentary age has a significant impact on the \(C_d\) value. For laboratory tests, newly deposited and natural sedimentary fine sands, the typical values of \(C_d\) are 35, 40, and 55, respectively. Based on the analysis of the high-quality undisturbed sample data obtained by the in-situ freezing method, Cubrinovski and Ishihara (1999) pointed out that the \(C_d\) of pure sand is 51 I.M. Idriss and R.W. Boulanger (2003) suggest that \(C_d\) is 46 to calculate the relative density of sand.

3.3. Estimation of relative density based on the number of SPT

According to the aforementioned SPT results and formulas (4)–(6), the relative density of each borehole can be calculated. It is worth noting that in the process of sorting out the actual measured SPT number \(N_m\), this article has considered the correction coefficient of the impact factors such as the energy conversion of the hammer, the aperture, the length of the rod, and the groundwater.

Based on the research results of Meyerhof (1957) and Skempton (1986), the constants \(a\) and \(b\) are closely related to the particle size, sedimentation age and consolidation characteristics of the sand. Generally, \(a=17, b=24\), and take \(C_d=a+b=41\) at the same time. The relative density is calculated with the above empirical parameters, and the result of the sorting is shown in Figure 3(1).

According to the statistical analysis of the result data (see Table 3), the average relative density is 0.49–0.51, which is much smaller than the measured relative density of 0.67-0.91 in situ. The reason may be that the sandy soil in this paper which is deeply buried and deposited for a long time, is different with the sand in the existing research. The empirical parameters \(a, b\) and \(C_d\) may not be applicable.
4. Corrected calculation of relative density

4.1. Parameter correction based on sand characteristics

4.1.1 Optimize constants $a$ and $b$. The normalization coefficient $C_N$ is related to the grain properties, occurrence conditions and consolidation characteristics of the soil layer. Formula (5) can be transformed to get formula (7), where $c = a/b$. Obviously the value of $c$ has a great influence on $C_N$.

$$C_N = \frac{1+c}{c + \sigma_v / p_s}$$  \hspace{1cm} (7)

After the above transformation, only the value of $c$ needs to be determined, which is more simplified than the original formula (5) to determine the two constants $a$ and $b$. Skempton (1986) showed that the value of $c = a/b$ of sand increases with the increase of the average particle size $d_{50}$ and the relative density $D_r$. In this paper, the $D_r$ of sand is $>0.4$, the average particle size $d_{50}$ is between 0.016mm to 1.8mm, and the average $d_{50}$ is 0.4mm. Among them, medium-coarse sand with gravel $d_{50}$, take $c = 2$; medium-fine sand $d_{50}$, take $c = 1$.

4.1.2 Grain size effect coefficient $C_d$. $C_d$ is related to the grain size of the soil layer. According to the study of Cubrinovski and Ishihara (1999), it can be obtained by the following formula

$$C_d = \frac{9}{(e_{\text{max}} - e_{\text{min}})^2}$$  \hspace{1cm} (8)

Where: $e_{\text{max}}$ and $e_{\text{min}}$ are the maximum and minimum void ratios.

Expressing $C_d$ as a function of the void ratio range ($e_{\text{max}} - e_{\text{min}}$), $C_d$ can be solved directly according to the physical test results, and it is not directly related to the constants $a$ and $b$, which helps to improve the calculation accuracy. A large number of borehole sampling tests have been carried out on the sand in this paper. Based on the results of 49 sets of physical tests, the distribution range of $C_d$ is 16.5-43.6, and the average value is 25.16.

4.1.3 Correction calculation of relative density. According to the above analysis, $c$ corresponds to the gravel-bearing medium-coarse sand and medium-fine sand with values of 2 and 1, respectively, and the average value of $C_d$ is 25. After parameter correction (ie, correction method 1st), the relative density is calculated. The results are shown in Figure 4.

According to the statistical analysis of the result data (see Table 3), the average relative density is 0.75-0.78, which is closer to the in-situ measured relative density of the boreholes of 0.67-0.91, which is much better than the calculation results with empirical parameters. It can be seen from Figure 3(2) that the calculated value of the relative density of each borehole is overall higher than that of Figure 3, and the distribution law along the depth direction is generally the same. Part of the boreholes (such as ZKm205 and ZKm306) appear as the depth increases, the relative density decreases, which is not consistent with the in-situ test results of the boreholes, and also deviates from the actual situation.

Table 3. Calculation results of $D_r$.

| Drilling No. | $ZKm104$ | $ZKm205$ | $ZKm306$ | $ZKm402$ |
|--------------|---------|---------|---------|---------|
| minimum      | $0.461/0.636^*$ | $0.449/0.618$ | $0.456/0.668$ | $0.410/0.662$ |
| maximum      | $0.563/0.845$ | $0.633/0.899$ | $0.516/0.802$ | $0.606/0.913$ |
| average      | $0.502/0.761$ | $0.514/0.769$ | $0.492/0.746$ | $0.500/0.781$ |

Note: $0.461/0.636^*$, 0.461 is the result with empirical parameters and 0.636 is the result with correction method 1st.

4.2. Correct the effective overburden pressure based on the critical depth

In this paper, the thickness of sand in layer 2nd is greater than 100m. According to the results of in-situ borehole tests, the structure and density of sand are generally uniform, and the natural density increases
slightly with depth overall. Therefore, the aforementioned calculations show that as the depth increases, the relative density calculated based on SPT decreases, which obviously does not conform to the physical characteristics of the deep-covered sand layer. This is due to the large sand buried depth in this paper, which exceeds the depth range of the existing research and may exceed the scope of application of the empirical formula.

According to the calculation principle of soil weight pressure, the influence depth of the upper soil body weight is limited, that is, as the buried depth increases, the influence of the upper soil body weight decreases. In the field test of this article, the \( N_m \) of SPT reached very little change in the deep soil layer, which also proved this point. Therefore, as the buried depth increases, the growth rate of the effective overburden pressure will decrease until it tends to a constant. At this time, the formula \( \sigma_{vo} = \sum \gamma_i h_i \) is inappropriate. For this reason, the effective overburden pressure of deep sand should be corrected.

According to the results of the SPT conducted on the deep-covered sand, the \( N_m \) of the sand in depth of 60m-70m increases relatively slowly, and the analysis shows that it is no longer suitable to use the formula \( \sigma_{vo} = \sum \gamma_i h_i \) to calculate the effective overburden pressure at this time. For this reason, 65m is considered as the critical depth. When the depth of the measuring point exceeds 65m, the effective overburden pressure in the formula will no longer increase, and it will always be equal to the effective overburden pressure at a depth of 65m. The corrected value is shown in Figure 3(3).

After taking the same \( c \) and \( C_d \) parameters as in section 4.1, after correcting the effective overburden pressure according to the above method (correction method 2\(^{nd}\)), the new relative density calculation results can be obtained, as shown in Figure 6. Comparing Fig. 6 and Fig. 4, it can be seen that the relative density of deep sand has increased after the correction calculation of the measuring point with a buried depth greater than 65m. The relative density results statistics of the buried depth greater than 65m (see Table 4) are carried out, and after the correction of the effective overburden pressure, the average value is 0.77 to 0.87, which is close to the 0.81 to 0.84 of the borehole test (see Table 1).

---

**Figure 3. Distribution graph of relative density along depth**

**Table 4.** \( D_r \) comparison for the sand buried depth greater than 65m.

| Drilling No. | ZKm104 | ZKm205 | ZKm306 | ZKm402 |
|-------------|--------|--------|--------|--------|
| empirical parameters | 0.495 | 0.466 | 0.497 | 0.421 |
| correction method 1\(^{st}\) | 0.740 | 0.715 | 0.736 | 0.678 |
| correction method 2\(^{nd}\) | 0.867 | 0.776 | 0.838 | 0.765 |
5. Influencing factors of the correction method

5.1. Influence of sand material composition

From the particle test of layer 2nd, the material composition is mainly gravel-bearing medium-coarse sand layer and medium-fine sand. The average particle size \(d_{50}\) ranges from 0.016mm to 1.8mm, and the average value is 0.4mm. Distributed as a cliff, the peak appears at the point near 0.3mm.

According to the particle size distribution of sand in layer 2nd, the primary analysis is that the gravel-containing medium-coarse sand is the main component. When estimating the relative density based on the SPT, the physical characteristics of the gravel-containing medium-coarse sand should be mainly used in the calculation parameters.

For sandy soil, the constant \(c\) value in formula (7) increases with the increase of the average particle size \(d_{50}\) and the relative density \(D_r\). According to the distribution range of the relative density and average particle size \(d_{50}\) of the sand in this paper, it is proposed to take \(c\) as 2 and 1 for the gravel-bearing medium-coarse sand and medium-fine sand, respectively. Considering the actual situation where gravel-bearing medium-coarse sand layers are dominated, \(c=2\) can be uniformly adopted for the convenience of calculation. For the empirical parameters \(a=17\) and \(b=24\) obtained in the existing research, \(c=a/b=0.71\), which is closer to silt fine sand, which is far from the gravel-containing coarse sand in this paper, so the relative density calculation results will be different very big.

For the \(C_d\) value, through a large number of indoor and field tests, it is agreed that the general sand \(C_d\) value is 35-55. According to formula (8), the \(C_d\) value is inversely proportional to the void ratio range \((e_{\text{max}}-e_{\text{min}})\). According to the analysis and calculation of the 49 groups of physical properties in this paper, the \((e_{\text{max}}-e_{\text{min}})\) distribution is 0.40-0.70, and the classification statistics can get the average \((e_{\text{max}}-e_{\text{min}})\) of the gravel-containing medium-coarse sand layer and medium-fine sand to be 0.62 and 0.48 respectively. The corresponding \(C_d\) values are 31 and 20, which are smaller than the recommended value range 35-55 of \(C_d\) in the existing research. The value of \(C_d\) has a great influence on the solution of relative density. It is necessary to correct the calculation of \(C_d\) according to the size and distribution of sand particles.

5.2. The influence of the sedimentary history of the overburden

The sedimentary history of the overburden has a great influence on its compactness. From the analysis of geological structure, topography, overburden distribution, hierarchical structure and material composition, it is concluded that the deep-covered sand layer in this paper is formed by natural riverbed sedimentation, which has a long history and has normal consolidation characteristics.

The empirical formula for calculating the relative density based on SPT is mainly based on indoor and on-site experiments. Studies have shown that the consolidation characteristics of sand have great differences with the overlying effective stress correction formula. Among them, the empirical formulas proposed by Seed (1985) and Skempton (1986) (see Table 5) all use soil consolidation characteristics as the applicable soil classification conditions for the formula.

| Name            | formula                   | Sand type                        | Name            | formula                   | Sand type                        |
|-----------------|----------------------------|----------------------------------|-----------------|----------------------------|----------------------------------|
| Seed (1985)     | \(N_i = \left(\frac{p_a}{\sigma_o}\right)^{1.3} N_s\) | Coarse sand, normal consolidation | Skempton (1986) | \(N_i = \frac{3}{2 + \sigma_o/p_s} N_e\) | Coarse sand, normal consolidation |
|                 | \(N_i = \frac{2}{1 + \sigma_o/p_s} N_e\) | Fine sand, normal consolidation  |                 | \(N_i = \frac{1.7}{0.7 + \sigma_o/p_s} N_e\) | Fine sand, over-consolidated      |

From the perspective of sand particle size and consolidation characteristics, this paper selects \(c=a/b=2\) (medium coarse sand) and \(c=1\) (medium fine sand) to calculate the normalization coefficient \(C_N\), which is in good agreement with the formula in Table 5.
6. Conclusion

Based on the results of 243 sets of SPT, the relative density is estimated by using the normalized empirical formula. Using empirical parameters to estimate the relative density of sand in this paper, the average value of each borehole is 0.49-0.51, and the total average value is about 0.50, which is far lower than 0.67-0.91 of the in-situ test results of boreholes, which cannot truly reflect the actual situation. So, this article uses a modified method to calculate:

1) Correction method 1st, the calculation parameters are corrected based on the physical properties of sand. Use \( c = \frac{a}{b} \) to transform the normalization coefficient \( C_N \) expression, reduce the number of constants, and determine the constant \( c \) and the grain size effect coefficient \( C_d \) based on the physical properties of the sand. With correction method 1st, the calculated average relative density is about 0.76, which is closer to the results of the in-situ density test and the indoor sampling test.

2) Correction method 2nd, to correct the effective overburden pressure based on the critical depth. The relative density calculated by the correction method 1st still has the situation that the relative density decreases as the buried depth increases. This is because the effective overburden pressure of the deep soil layer in the formula is overestimated. According to the calculation principle of soil mechanics, the influence of the upper soil weight on the effective overburden pressure has a critical depth, and the influence is small or negligible after the critical depth is exceeded. According to the distribution law of the standard penetration number, 65m is used as the critical depth to correct the effective overburden pressure, which improves the unreasonable law of the relative density result with excessive increase in depth. With correction method 2nd, the calculated average relative density is 0.79, which is consistent with the in-situ density test results closer.

References

[1] Liu, X. S., Zhao Dong, Z., Wang, W. S. Experimental study on the influence of undisturbed structure on the dynamic deformation characteristics of saturated sand [J]. Journal of Hydraulic Engineering, 1993, 2: 32-42. In Chinese.

[2] Jiang, S. T. Comparison of dynamic strength characteristics of undisturbed sand and disturbed sand on two foundations [J]. Dam Observation and Geotechnical Testing, 1991, 15(1): 31-36. In Chinese.

[3] Terzaghi, K, and Peck, R B. Soil Mechanics in Engineering Practice [M]. New York: Wiley, 1948

[4] Gibbs, H J & Holtz, W G. Research on Determining the Density of Sands by Spoon Penetration Testing [C]/Proceedings, Fourth International Conference on Soil Mechanics and Foundation Engineering, London, 1957, 1: 35-39,

[5] Bieganousky, W A & Marcuson, W F. Laboratory standard penetration tests on Reid Bedford model and Ottawa sands.Research [R] Report S-76-2no.1,Waterways Experiment Station,Vichsburg,1976.

[6] Saito, A. Characteristics of penetration resistance of a reclaimed sandy deposit and their change through vibratory compaction [J]. Soils and Foundations,1977,17(4):31-43

[7] Ishihara, K & Koga, Y. Case studies of liquefaction in the 1964 Niigata earthquake [J]. Soils Found., 1981, 21(3), 35–52.

[8] Meyerhof, G G. Discussion on research on determining the density of sands by spoon penetration testing [C]/Proc.4th Int.Conf.Soil Mech. Fdn Engng, London. 1957;3:110.

[9] SKEMPTON A W. Standard penetration test procedures and the effects in sands of overburden pressure, relative density, particle size, aging and overconsolidation [J]. Geotechnique, 1986,37(3):425-447

[10] CUBRINOVSKI M, Ishihara K. Empirical correlation between SPT N-value and relative density for sandy soils[J]. Soils and Foundations, 1999, 39(5): 61-71

[11] Boulanger, R W. High overburden stress effects in liquefaction analyses [J]. J. Geotechnical and Geoenvironmental Engineering, ASCE, 2003,129(12):1071-1082.

[12] ASTM D1586-11, Standard Test Method for Penetration Test and Split barrel sampling of soils.
[13] Seed H B, Tokimatsu K, Harder L F, et al. 1985. Influence of SPT Procedures in soil Liquefaction Resistance Evaluations[J]. Journal of Geotechnical Engineering, 111(12): 1425-1445