Seismic liquefaction evaluation of deposit soils under engineering loading or unloading conditions

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Abstract. Engineering activities such as water conservancy and hydropower, water transportation and harbor and navigation often lead to loading or unloading conditions, which makes the stress state of overlay different before and after construction. Relevant codes in the field of water conservancy and hydropower projects recommend the linearization correction method based on stress equivalence expressed by buried depth, considering the influence of stress state of overlying soil on its liquefaction resistance under loading and unloading conditions. On the basis of demonstration and analysis, this paper points out that the linearization correction method based on stress equivalence expressed by buried depth will overestimate the anti-liquefaction ability of soil under engineering loading conditions, and the liquefied layer may be evaluated as non-liquefaction, which brings potential risks to the project. Under unloading conditions, the anti-liquefaction capacity of soil will be underestimated, and the non-liquefied layer may be evaluated as liquefaction, which will lead to the increase of foundation treatment cost. Aiming at the defect of linearization correction method based on stress equivalence expressed by buried depth, a new non-linearization correction method is proposed, which takes into account the influence of the stress state of overburden soil caused by loading and unloading of dams and other projects on its liquefaction resistance. This method can effectively avoid the potential danger or waste of investment caused by the miscalculation of the original formula.

1. Introduction

In the construction of water conservancy and hydropower projects, water transport projects, port and harbor projects, and civil and industrial construction projects (such as airports) on river alluvial plains, deep cover problems are often encountered. For the overburden foundation, water conservancy and hydropower engineering, water transport engineering and port and harbor engineering construction activities often lead to the emergence of loading or unloading conditions, making the stress conditions of the overburden layer before and after the construction different, that is, the stress conditions of the overburden foundation in the survey and design stage of the project are different from the stage under the application conditions after the completion of the project. For example, in the engineering construction of water circulation control and hydropower resources development upper damming basin of the overburden, it is often encountered overburden soil loading caused by high filling or
overburden soil unloading caused by deep excavation. For the water-retaining construction, the groundwater level near the project site will also increase after the construction of the project. Before and after the construction of the project, the ground elevation and groundwater level change greatly, resulting in changes in the stress conditions of the corresponding parts of the overburden. Similarly, in the construction of airports on river alluvial plains, engineering loading and unloading conditions of the large-scale excavation and filling often take place. When the basic seismic intensity on the project site is high and the soil in the overburden is sensitive to seismic loads, the seismic liquefaction stability of the overburden is a concern of the project construction. This requires evaluation on the seismic liquefaction stability of the overburden foundation in the normal operation phase after the construction during the survey and design stage of the project. That is, the seismic liquefaction evaluation is carried out under the condition that the stress conditions of the soil in the overburden layer are changed due to engineering loading and unloading of the damming and other engineering.

Aiming at the situation that the stress conditions of the overburden foundation are often changed due to loading or unloading caused by engineering activities in the construction of water conservancy and hydropower projects, Mr. Wang Wenshao recommended the formula (1) to collect the actually measured standard penetration test (SPT) blow count in the Anti-seismic Design Code of Hydraulic Structures (SDJ10-78). The corrected SPT blow count was compared with the liquefaction critical SPT blow count under the operating conditions after the completion of the project, to determine the possibility of liquefaction of the original standard penetration test point under the operating conditions after the completion of the project. Therefore, whether the correction of the measured SPT blow count could better reflect the influence of the stress condition on the SPT blow count is directly related to engineering safety.

In the case of setting a standardized overburden homogeneous sand layer model (the groundwater level $h_w$ was 2m, the natural bulk density of the sand layer was 18kN/m$^3$, and the saturated bulk density was 19kN/m$^3$), formula (1) can be transformed into the form shown as formula (2). The current code (GB 50487-2008) stipulates that when the depth of the penetration point in the standard penetration test and the groundwater level are below depth of the test ground, different from the operation after the completion of the project, the actually measured SPT blow count shall be corrected in accordance with formula (3), and the corrected SPT blow N should be used as the basis of reconsideration.

$$N = N' \left( \frac{p}{p_a} + 0.7 \right)$$  \hspace{1cm} (1)

$$N = N' \left( \frac{d_s + d_w + 7.8}{d_s + d'_w + 7.8} \right)$$  \hspace{1cm} (2)

$$N = N' \left( \frac{d_s + 0.9d'_w + 0.7}{d_s + 0.9d_w + 0.7} \right)$$  \hspace{1cm} (3)

where: $N$ - the corrected SPT blow count, which represents SPT blow count of the original test point when the groundwater level and ground elevation were changed after the completion of the project; $N'$ - the SPT blow count of the standard penetration test point before the construction; $p$ - the effective overlying stress of the original standard penetration test point under the change of groundwater level and ground elevation after the completion of the project, kPa; $p_a$ - the effective overlying stress of the standard penetration test point before the construction of the project, kPa; $d_s$, $d'_s$ - the depths (m) of the standard penetration point below the ground at the time of operation and standard penetration test after the completion of the project, respectively; $d_w$, $d'_w$ - the depth (m) of the groundwater level below the ground at the time of operation and standard penetration test after the
completion of the project (m), respectively, and when the ground is submerged below the water surface, the value is 0.

Formula (1) reflects the effect of stress conditions on the SPT blow count. From the evolution of the standard formula (1) to formula (3), it can be seen that the formula (3) still substantially reflects the influence of the stress condition on the SPT blow count. In practical engineering applications, it is found that when engineering loading taking place in engineering activities leads to the increase of the overburden effective stress on the overburden soil, the SPT blow count obtained by the formula (3) seems to be too large. The liquefaction occurs when the liquefaction possibility is judged according to the standard penetration test point stress condition in the standard penetration test, and the liquefaction no longer takes place after the engineering loading happens in the engineering activities, which leads to the increase of the overburden effective stress on the overburden layer. When engineering loading happened in engineering activities leads to the decrease of the overburden effective stress on the overburden soil, the SPT blow count obtained by the formula (3) seems to be too small. The liquefaction does not take place when the liquefaction possibility is judged according to the standard penetration test point stress condition in the standard penetration test, and the liquefaction occurs after the engineering loading happens in the engineering activities, which leads to the decrease of the overburden effective stress on the overburden layer. Therefore, it is necessary to examine the applicability of formula (3) under the conditions of engineering loading and unloading.

This paper systematically summarizes the domestic and overseas research results of the influence of stress conditions and compact state on SPT blow count, and based on the SPT in the seismic liquefaction field and the test results of the indoor full-scale standard penetration model, the effects of stress conditions and compact state on the SPT blow count are investigated. Besides, aiming at the loading and unloading conditions (working conditions) encountered in engineering, the linearization correction method based on stress equivalence expressed by buried depth in the original specification is demonstrated. Under the engineering loading conditions, the soil liquefaction resistance is overestimated, and the liquefaction layer is likely to be judged as non-liquefied, which will bring potential risks to the project. Under the condition of engineering unloading, the anti-liquefaction ability of the soil will be underestimated, and the non-liquefaction layer may be judged as liquefied, resulting in an increase in the cost of foundation treatment. In view of the defects of the method in the original specification, on the basis of the argumentation analysis, a new nonlinear correction method is proposed to consider the influence of the change of the overburden solid stress conditions on the liquefaction resistance of the soil due to the loading and unloading of the dam.

2. Influence of overburden effective stress and relative density on SPT blow count

In practical engineering applications, the measured SPT blow count under different overburden effective stress in the overburden foundation soil is normalized to the SPT blow count under the effective stress of 100 kPa, which is denoted by the formula (4).

\[
(N_l)_{100} = C_N N'
\]

where: \((N_l)_{100}\) - SPT blow count at 100 kPa; \(C_N\) - normalization coefficient of overburden effective stress.

On the basis of the indoor full-scale standard penetration model or based on the SPT on the overburden site, different researchers proposed normalized coefficient correction formulas of different overburden effective stress. The article [1] first established the relationship between the mechanical index of overburden sand soil, SPT blow count, and the sand compaction state index, the relative density. Since then, the article [2] and [3] carried out indoor full-scale penetration tests on different sands with different stress conditions and at different density states. The article [4] performed on-field penetration tests on the fine sand packing layer on the island, and the article [5] carried out on-field penetration tests on the seismic sand foundation of Niigata in Japan in 1964. The results of the indoor full-scale penetration model test and the field penetration tests further proved that the penetration blow
count is closely related to the relative density and stress conditions: When the stress conditions of the overburden sand are the same, the penetration blow count and the relative density are positively correlated; When the physical state (relative density) of the overburden sand is the same, the penetration blow count and the overburden effective stress are positively correlated. According to the results of overburden sand penetration tests under different relative density and different overburden effective stress, the article [6] firstly proposed the relationship between the penetration blow count, the relative density and the stress condition as the formula (5):

\[
\frac{N'}{D_r^2} = a + b \frac{\sigma'_{\nu_0}}{p_a}
\]  

(5)

where: \(N_m\) — measured penetration blow count; \(D_r\) — relative density; \(\sigma'_{\nu_0}\) — the overburden effective stress of the penetration point when the penetration test is performed, kPa; \(p_a\) — atmospheric pressure; \(a\) and \(b\) — test constants, both increase with increasing particle size, deposition age, and over consolidation ratio. Wherein, the relative density \(D_r\) is between 0.35 and 0.85 and the overburden effective stress \(\sigma'_{\nu_0}\) is between 50 kPa and 250 kPa.

2.1 Influence of overburden effective stress
For the sand layer of the same homogeneous overburden foundation, the relative density is the same. From formula (5), the expression of the SPT blow count after correction in the case of engineering loading or unloading can be derived.

\[
N = \frac{a / b + \sigma'_{\nu_1} / p_a}{a / b + \sigma'_{\nu_0} / p_a} N'
\]  

(6)

where: \(\sigma'_{\nu_1}\) — the effective overlying stress of the original standard penetration test point under the conditions of engineering loading or engineering unloading, kPa.

Let \(\sigma'_{\nu_1}=100\) kPa in the formula (6), then the formula (6) is converted into the same form as the formula (4).

\[
(N_i)_{60} = \left( \frac{a / b + 1}{a / b + \sigma'_{\nu_0} / p_a} \right) N'
\]  

(7)

That is

\[
C_N = \left( \frac{a / b + 1}{a / b + \sigma'_{\nu_0} / p_a} \right)
\]  

(8)

Meyerh of (1957) [6] suggested \(a/b=1.71\) based on test data, Tokimatsu et al. (1983) [7] suggested \(a/b=0.7\), which is in the range of \(a/b=0.6-0.8\) for over consolidated sand. Skempton (1986) [9] suggested that \(a/b = 1.0\) for medium-density fine sand in normal consolidation state, \(a/b=2.0\) for compact coarse sand in normal consolidation state, and \(a/b = 0.6-0.8\) for over consolidated soil. Kayen et al. (1992) [12] suggested \(a/b=1.2\) for medium-density sand, which was recommended to be used in the NCEER method (improved Seed method) by Youd et al. (2001) [11] to determine the seismic liquefaction of sand and calculate \(C_N\).

Peck et al. (1974) [7], Seed (1976), and Seed (1983) [8] respectively recommended to utilize the formula (9), formula (10), and formula (11), to calculate the overburden effective stress normalization coefficient \(C_N\).
Under the condition that the overburden soil is homogeneous sand, combined with the formula (4),
the formula (12) to (14) can be derived from the formula (9) to (11).

\[ C_N = 0.771 \lg \left( 20 \cdot \frac{p_a}{\sigma'_{v0}} \right) \quad (9) \]
\[ C_N = 1 - 1.25 \lg \frac{\sigma'_{v0}}{p_a} \quad (10) \]
\[ C_N = \left( \frac{p_a}{\sigma'_{v0}} \right)^{1/2} \quad (11) \]

2.2 Influence of sand relative density

Seed (1983) \cite{8} proposed to use the overburden effective stress correction as shown in Table 1, on the
basis of the data analysis by Bieganousky et al. (1976) \cite{3} of sand penetration test under different stress
conditions and different compact states.

| \( \sigma'_{v0} \) /kPa | 50  | 75  | 100 | 150 | 200 | 250 | 300 |
|-----------------------|-----|-----|-----|-----|-----|-----|-----|
| \( D_r = 40\% \sim 60\% \) | 1.36 | 1.14 | 1   | 0.8 | 0.69| 0.6 | 0.54 |
| \( D_r = 60\% \sim 80\% \) | 1.36 | 1.14 | 1   | 0.84| 0.74| 0.67| 0.61 |

Skempton (1987) reanalyzed the experimental data on the basis of formula (9) and proposed a
formula (15) that is of more general meaning than formula (11).

\[ C_N = \left( \frac{p_a}{\sigma'_{v0}} \right)^{m} \quad (15) \]

where \( m \) is a function of relative density. Boulanger (2003) \cite{13} analyzed the SPT data of Marcuson et
al. (1977) \cite{14,15} and found that \( m \) has a linear relationship with relative density \( D_i \).

\[ m = 0.784 - 0.521D_i \quad (16) \]

Combined with formula (4), formula (16) can be derived.

\[ N = \left( \frac{\sigma'_{v1}}{\sigma'_{v0}} \right)^{m} \cdot N' \quad (17) \]

When the relative density \( D_i = 54\% \), \( m = 0.5 \), and then formula (17) is transformed to formula (14).
According to the analysis, under the conditions of engineering loading and unloading, the corrections of the original SPT blow count are linear by formula (1), (2), (3), (6), (14) and (15).

2.3 Comparison of the effects of overburden effective stress and relative density on SPT blow count

In order to compare the different formulas describing the relationship between the overburden effective stress and the relative density, a homogeneous sand layer model for standardized overburden foundation was set, with a thickness of 40 m and a groundwater level of 2.0 m. The natural bulk density and saturated bulk density of the sand layer above the groundwater level and below the groundwater level were 18kN/m$^3$ and 19kN/m$^3$, respectively, while the SPT blow count at 100kPa was 24.5 hits. According to the formulas recommended by different scholars, the SPT blow count at 100 kPa can be converted into the corresponding SPT blow count under the conditions of different depth and overburden effective stress, as shown in Table 2, and N~$\sigma_{vo}$ curve as shown in Fig. 1 can be obtained.

| $\sigma_{vo}$ | Formula (6) | Formula(12) | Formula(13) | Seed(1983) | Formula (17) |
|--------------|-------------|-------------|-------------|------------|-------------|
| a/b          | Dr          | Dr          | Dr          | Dr         | Dr          |
| 0.7          | 1           | 1.2         | 2           | 40-60%     | 60-80%      |
| 25           | 13.7        | 15.3        | 16.4        | 14.0       | 10.2        |
| 50           | 17.3        | 18.4        | 18.9        | 20.4       | 19.9        |
| 75           | 20.9        | 21.4        | 21.7        | 22.5       | 22.3        |
| 100          | 24.5        | 24.5        | 24.5        | 24.5       | 24.5        |
| 125          | 28.1        | 27.6        | 27.3        | 26.5       | 26.4        |
| 150          | 31.7        | 30.6        | 30.1        | 28.6       | 28.3        |
| 175          | 35.3        | 33.7        | 32.9        | 30.6       | 30.1        |
| 200          | 38.9        | 36.8        | 35.6        | 32.7       | 31.8        |
| 225          | 42.5        | 39.8        | 38.4        | 34.7       | 33.5        |
| 250          | 46.1        | 42.9        | 41.2        | 36.8       | 35.2        |
| 275          | 49.7        | 45.9        | 44.0        | 38.8       | 36.9        |
| 300          | 53.3        | 49.0        | 46.8        | 40.8       | 38.6        |
| 300          | 53.3        | 49.0        | 46.8        | 40.8       | 38.6        |
| 300          | 53.3        | 49.0        | 46.8        | 40.8       | 38.6        |
| 300          | 53.3        | 49.0        | 46.8        | 40.8       | 38.6        |
| 300          | 53.3        | 49.0        | 46.8        | 40.8       | 38.6        |
| 300          | 53.3        | 49.0        | 46.8        | 40.8       | 38.6        |
| 300          | 53.3        | 49.0        | 46.8        | 40.8       | 38.6        |

Figure 1. Standard penetration number under different overlying effective stress conditions.

It can be seen from the analysis of Table 2 and Fig. 1 that, in the common overburden effective stress range (50–300kPa) in the seismic liquefaction case of sand layer: The formulas that do not consider the influence of relative density are only applicable to sands at specific states such as loose,
medium-density or compact. At a certain relative density of the sand, the \( N - \sigma'_{cv} \) curve calculated by the formula (17) is close to the relationship curve between the SPT blow count and the overburden effective stress calculated by the formulas recommended by different scholars. If the curve is calculated by the formula (12) and the relative density in the formula (17) is 75\%, the calculated curves are close when the overburden effective stress is greater than 100 kPa. In formula (6), if the value of \( a/b \) is 0.7, 1.0, 1.2, and 2.0, respectively, the calculated curves are close to those when the formula (17) take relative density of 30\%, 35-40\%, and 45\%,65\%, respectively. The calculated curves when the correction results of the relative density recommended by Seed are 40\%-60\% and 60\%-80\%, are close to those when the relative density in formula (17) is 45\% and 65\%. Therefore, the formula (17) established on the basis of different overburden effective stress and the standard penetration test data of the sands at different relative density, can better describe the influences of relative density and stress conditions on the SPT blow count, and is suitable for sands at different density states.

It can be seen from Table 2 and Fig. 1 that, in general, when the overburden effective stress of the overburden soil caused by the engineering loading happened in the engineering activities increases, the denser the sands, the bigger the SPT blow count obtained by different formulas corrected to the same overburden effective stress. When the overburden effective stress of the overburden soil caused by the engineering loading happened in the engineering activities decreases, the denser the sand, the smaller the SPT blow count obtained by different formulas corrected to the same overburden effective stress. In same kind of formulas, the change trends of correction to the two directions are reversed. However, in practical engineering, it is difficult for engineering design and geological survey workers to choose different formulas to correct according to the actual state of the sand layer. In order to facilitate the application, it is necessary to combine the actual conditions of the project construction to investigate the rationality of the proposed project and propose reasonable correction formulas based on the argument.

3. Comparison of seismic liquefaction evaluation methods for overburden under the conditions of engineering loading and unloading
The ratio of the corrected SPT blow count \( N \) corresponding to the overburden effective stress on the standard penetration test point in the engineering application to the actually measured SPT blow count \( N \) at corresponding test point, is defined as the correction coefficient \( C_N \) of the overburden effective stress. The corrected SPT blow count \( N \) corresponding to the overburden effective stress in the operation conditions after the completion of the project can be expressed as:

\[
N = C_N N'
\]  

As can be seen in the formula (18), \( N \) is proportional to \( C'_N \), and the larger \( C'_N \) is, the larger \( N \) is. When the corrected \( N \) is used to evaluate the liquefaction of the overburden sand foundation, the liquefaction evaluation result tends to be insecure. On the contrary, it tends to be secure.

According to the standard formula (3), it can be obtained:

\[
C'_N = \left( d_r + 0.9d_w + 0.7 \right) / \left( d_r + 0.9d_w + 0.7 \right) 
\]  

It can be obtained from formula (17)

\[
C'_N = \left( \sigma'_{cv} / \sigma'_{so} \right)^m
\]  

It can be seen from the foregoing discussion that the formula (17) can better describe the relationship between the SPT blow count and the relative density and the overburden effective stress, with a wide application scope. Therefore, this section compares formula (20) with formula (19) to demonstrate the applicability of the standard formula.
The above-mentioned assumed homogeneous sand layer is still used as the analysis object, and the variation of the SPT blow count with the overburden effective stress after the correction of the dam under the conditions of engineering loading and unloading is investigated. The investigation includes two working conditions: 1) engineering loading, that is, engineering loading happened in the engineering activities leads to an increase of the overburden effective stress on the overburden soil. For example, in order to enhance the stability of the dam slope after the earth dam is built or to improve the seismic stability of the overburden near the foot of the dam, the measures such as weighting the slope toe are adopted. Or the reduction of the groundwater level after the completion of the project leads to an increase in the overburden effective stress of the original standard penetration test point, and or the overburden effective stress enlarges due to the loading of the filling project during the construction; 2) Engineering unloading, that is, engineering unloading happened in the engineering activities leads to an decrease of the overburden effective stress on the overburden soil. For example, after the completion of the project, the increase of the groundwater level will result in the reduction of the overburden effective stress, and the excavation unloading may happen. For ease of understanding, the increase or decrease of the overburden effective stress is equivalent to the buried depth of the standard penetration test point.

3.1 Engineering loading

Here two situations are provided: 1) After the completion of the project, the engineering loading is caused by the increase of the overburden effective stress on the original test point due to the drop of the groundwater level; 2) During the construction of the project, the engineering loading is caused by the increase of the overburden effective stress on the original standard penetration test point due to the filling.

As a typical example, two cases are given. Assuming that before the construction of the project, the buried depth of the test point in the standard penetration test is 10 m and the groundwater level is 2 m. When the drop of the groundwater level after the completion of the project gives rise to engineering loading, the variation of overburden effective stress correction coefficient is shown in Fig. 2(a). Before the construction of the project, the buried depth of the test point is 3 m, and the groundwater level is 2 m. The variation of the overburden effective stress correction coefficient under engineering loading caused by the increase of the overburden effective stress due to the filling in the project construction is shown in Fig. 2(b).

![Figure 2. Variation of overburden effective stress correction coefficient under engineering loading.](image)

The shallow buried sand layer in the actual occurrence state has a small overburden effective stress, usually in a looser state below the medium density ($D_r<55\%$). Under the condition of engineering loading, the looser the sand, the larger the overburden effective stress correction coefficient. Therefore, when engineering loading occurs, the correction coefficient of the overburden effective stress calculated by formula (20) based on a slightly denser relative density ($D_r=55\%$) than the actual state.
3.2 Engineering unloading

Two situations are provided here: 1) After the completion of the project, the engineering unloading is caused by the increase of the overburden effective stress on the original test point due to the rising of the groundwater level; 2) During the construction of the project, the engineering loading results from the decrease of the overburden effective stress on the original standard penetration test point due to excavation.

As a typical example, two cases are given. Assuming that before the construction of the project, the buried depth of the test point in the standard penetration test is 20 m and the groundwater level is 20 m. When the rising of the groundwater level after the completion of the project gives rise to engineering loading, the variation of overburden effective stress correction coefficient is shown in Fig. 3(a). Before the construction of the project, the buried depth of the test point is 20 m, and the groundwater level is 2 m. The variation of the overburden effective stress correction coefficient under engineering unloading caused by the decrease of the overburden effective stress due to the excavation in the project construction is shown in Fig. 3(b).

It can be seen from Fig. 3 that, in the case of engineering unloading, when they are corrected to the same overburden effective stress, the value of \( C_N' \) calculated by the formula (20) increases with the increasing relative density, and the value of \( C_N' \) calculated by the correction formula (19) is significantly smaller than that calculated by formula (20) \( (D_r=30\%) \). As can be seen, under the condition of engineering unloading, if the actually measured SPT blow count is corrected by the formula (3) in the liquefaction evaluation, the result tends to be more insecure than the corrected result calculated by the formula (16) at the loose state \( (D_r=30\%) \). Therefore, under the condition of engineering unloading, the standard formulas tend to be conservative.

4. Discussion on seismic liquefaction evaluation method for overburden sand soil under the conditions of engineering loading and unloading

Based on the results of the dynamic residual deformation test of the reinforced soil, the changes of the axial residual strain and the volumetric residual strain with the vibration cycle, the consolidation confining pressure, the consolidation stress ratio, and the dynamic shear stress ratio were studied.

4.1 Engineering loading

In the practical engineering, for the shallow buried sand layer, during the construction of the project, it is either excavated or filled caused by engineering loading (such as the adjacent sand layer caused by weighting the slope toe). At this time, the value of \( C_N' \) calculated by the standard correction formula (19) is significantly larger than that calculated by the formula (20) in the loose state \( (D_r=30\%) \). Meanwhile, when engineering loading happens, the value of \( C_N' \) calculated by formula (20) decreases with the increasing relative density. Therefore, the linearization correction method based on stress
equivalence expressed by buried depth in the code during engineering loading, tends to be insecure to correct the actually measured SPT blow count of the overburden soil considering the influence of the overburden effective stress.

The shallow buried sand layer in the actual occurrence state has a small overburden effective stress, usually in a looser state below the medium density \((D_r < 55\%\)). Under the condition of engineering loading, the looser the sand, the larger the overburden effective stress correction coefficient. Therefore, when engineering loading occurs, the correction coefficient of the overburden effective stress calculated by formula (20) based on a slightly denser relative density \((D_r = 55\%)\) than the actual state.

4.2 Engineering unloading

In the practical engineering, for the deep buried sand layer, during the construction of the project, engineering unloading caused by excavation is often encountered. At this time, the value of \(C'_N\) calculated by the correction formula (19) in the code is significantly smaller than that calculated by the formula (20) in the loose state \((D_r = 30\%)\). In the meantime, when engineering unloading occurs, the value of \(C'_N\) calculated by formula (20) increases with the increasing relative density. Therefore, the linearization correction method based on stress equivalence expressed by buried depth in the code during engineering loading, tends to be conservative to correct the actually measured SPT blow count considering the influence of the overburden effective stress.

The deep buried sand layer in the actual occurrence state has a quite large overburden effective stress, usually in a compact state above the medium density \((D_r > 55\%)\). Under the condition of engineering unloading, the looser the sand, the smaller the overburden effective stress correction coefficient. Therefore, when engineering unloading occurs, the correction coefficient of the overburden effective stress calculated by formula (20) based on a slightly looser relative density \((D_r = 55\%)\) than the actual state.

5. Conclusion

This paper systematically summarizes the relevant research results of the overburden effective stress normalization coefficient determined in the on-site standard penetration test and the indoor full-scale standard penetration model test, deduces the correction formulas of the SPT blow count under the conditions of loading and unloading in the engineering activities such as dam construction, and combining with the correction method for the SPT blow count under the conditions of dam loading and unloading in relevant codes in the field of water conservancy and hydropower engineering, demonstrates the relationship between the SPT blow count and the overburden effective stress and relative density. On this basis, it is pointed out that the correction method for the SPT blow count under dam loading and unloading in relevant codes probably leads to misjudgment of the sand layer liquefaction or not. On the basis of argumentation, the new correction method instead of the original method is suggested to be utilized to evaluate the seismic liquefaction of the overburden sand soil under the condition of engineering loading and unloading.

(1) Under the condition of homogeneous sand layer, the relationship between the SPT blow count and the overburden effective stress is nonlinear. The linearization correction method based on stress equivalent expressed by the buried depth cannot truly reflect the influence of engineering loading and unloading on SPT blow count. Under the condition of engineering loading, the liquefaction resistance of the soil will be overestimated, and the liquefaction layer may be judged as non-liquefied, which brings potential risks to the project. Under the condition of engineering unloading, the liquefaction resistance of the soil will be underestimated, and the non-liquefaction layer may be judged as liquefied, resulting in an increase in the cost of foundation treatment.

(2) Through the investigation of the homogeneous sand layer, it is shown that in the nonlinear method, aiming at the defect of linearization correction method based on stress equivalence expressed by buried depth, a new non-linearization correction method is proposed, which takes into account the influence of the stress variation of overburden soil caused by loading and unloading of dams and other
projects on its liquefaction resistance. This method can effectively avoid the potential danger or waste of investment caused by the miscalculation of the original formula.

(3) In the practical engineering construction, the shallow buried sand layer in the medium-density and loose state usually undergoes engineering loading, and the deep buried sand layer in the medium-density and dense state usually undergoes engineering unloading. The demonstration shows that the results that the actually measured SPT blow count considering the influence of engineering loading and unloading is corrected by the formula $C_N' = \left( \frac{\sigma_{vl}}{\sigma_{vo}} \right)^{1/2}$ (corresponding to Dr=55%) and the seismic liquefaction of the overburden sand soil during the operation of the project is evaluated, trend to be secure.

(4) It is recommended to revise the seismic liquefaction evaluation method of the overburden under the condition of overburden effective stress change in the current codes of the water conservancy industry, so as to more reasonably consider the influence of engineering and unloading conditions on the seismic liquefaction of the overburden, and avoid potential risks or unnecessary investment waste caused by misjudgment.

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