A SIMPLIFIED METHOD FOR EVALUATING THE EFFECTIVENESS OF COMPACTION PILES IN SANDS CONTAINING FINES

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ABSTRACT

A simplified method is proposed to estimate the improvement effect achieved with various compaction piles for sandy soils containing fines. It is indicated that the main factors affecting the compaction effect are: 1) initial soil conditions such as initial density and fines content, 2) effective overburden pressure, 3) replacement ratio (defined as the ratio of the volume replaced by the pile to the unit volume of in situ soil), 4) ground surface swelling, and 5) non-uniform densification. Based on analysis of extensive field data and previous studies, several empirical relationships incorporating the factors stated above were established. With this method, the improvement effect can be estimated by comparing the normalized SPT N -values before and after improvement. The estimated results have been compared favorably with those obtained from field investigations. It was confirmed that the suggested method can be adopted in the actual design of various compaction piles.

Key words: case study, design, fines content, penetration test, sand compaction pile, silt, soft ground (IGC: K14)

INTRODUCTION

Sand compaction piles, quicklime piles and pile driving have been used extensively to densify sandy soils, such as coastal plain sediments, granular hydraulic fills, reclaimed and alluvial soils in order to increase the soil bearing capacity; to reduce possible foundation settlements; and particularly to increase soil resistance against liquefaction. The effectiveness of these methods in the improvement of sandy soils has often been reported in the literature (e.g., Ohsaki, 1970; Solymer et al., 1986; and Sato et al., 1993).

Studies on the method of estimating the improvement effect with various compaction piles, particularly for sandy soils containing fines, are quite few, although some methods have been proposed by Ogawa and Ishido (1965), Mizuno et al. (1987) and Shamoto et al. (1991 and 1995). Sufficient attention has not been paid to both the mechanism regarding the compaction and the factors affecting the improvement effect in the existing studies. A simplified, but reliable method of evaluation for the purpose of meeting actual design needs is still required.

The objective of this study was, initially, to briefly review the existing studies, and then to propose a simplified method of evaluation suitable for estimating the improvement effect achieved with various compaction piles for

sandy soils containing fines. The proposed method was developed on the basis of 1) understanding the densification mechanism of compaction piles, 2) analysis of various factors affecting the improvement effect, 3) the previous empirical relationships, and 4) extensive field test data. A chart that incorporates the correlation between the pre- and post-compaction SPT N -values over a wide range of fines content of less than 40% and the "replacement ratio" from 0.05 to 0.15 was provided for practical design of compaction piles. Good agreement between the estimated N -values and those measured after improvement suggests that the method can be used in the actual design of various compaction piles for the improvement of sands containing fines.

EXAMPLE OF GROUND IMPROVEMENT PROGRAMS

Sites and Soil Conditions

A great deal of data used in the present study came from extensive in situ investigations including standard penetration and laboratory tests before and after compaction pile installation. The fifteen sites which were investigated cover different regions of Japan. In order to check the effectiveness of the previous and present methods of estimating the compaction effect, a typical example of the

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test programs, which were performed at two project sites located in Chiba Prefecture near Tokyo Bay, are shown in Fig. 1.

Exploratory borings were made at Sites A and B shown in Fig. 1. Figure 2 shows typical boring logs from No. 1 through No. 6. The subsoil profile consists mainly of fine sands and silty fine sands down to a depth of 25 m below the ground surface, and also contains a small quantity of silt and clay. The soil to a depth of about 5 m consists of backfill with wet densities of 1.6 to 1.8 g/cm³. The underlying soil in the range from 5 m to 25 m was alluvial deposits of the Holocene epoch with wet densities of 1.6 to 2.0 g/cm³. Such soil conditions are usually found in the coastal reclaimed subsoil of Tokyo Bay. All the grain size distribution curves lie within the shaded zones shown in Fig. 3. Except for the clays, the fines contents range from about 5% to 70%.

The ground water table was not deeper than 3 m for all the sites, and therefore, almost the entire soil mass was saturated.

Fig. 1. Location of exploratory borings

Fig. 2. Typical boring logs

Fig. 3. Typical grain size distribution curves for the soils sampled at different depths

Sand Compaction Piles

Sand compaction piles were installed to densify the soils under the complete building areas in order to improve the safety of the sites against liquefaction and to reduce possible foundation settlements. A square grid pattern of piles 0.7 m in diameter with a 2-m spacing on centers was used throughout. The piles were driven vertically to the predetermined depths shown in Fig. 2.

Standard Penetration Tests (SPT) were performed at the centroid of each four-pile group before and after improvement in order to estimate the effect of compaction. The variation of the N -values along the depths is shown in Fig. 2 in which the solid and broken curves correspond to the penetration resistances before and after compaction. Comparison between the two curves indicates that the increase in penetration resistance due to densification averages about 10 blows per 0.3 m in the fine sands, indicating significant compaction effect. The increase in penetration resistance due to compaction is reduced however with an increase in the fines content.

COMPACTION EFFECT AND EXISTING METHODS OF EVALUATING IT

Compaction Effect and Replacement Ratio a_s

The effect of densification with compaction piling depends mainly on the volume of the piles forced into the subsoil profile. Usually, the volume replaced is measured by an index called "replacement ratio, a_s ", whose physical meaning is illustrated in Fig. 4, in which e_o and e'_o are the void ratio before and after compaction, respectively, and the replacement ratio is defined as

$$a_s = \frac{\Delta e}{1 + e_o} \quad (1)$$

Fig. 4. Physical relationships for replacement ratio a_s

Fig. 5. Typical layout of compaction piles and definition of replacement ratio a_s

In the practical design of compaction piles, the replacement ratio a_s may be determined for a unit depth, as demonstrated in Fig. 5, by the following equation.

$$a_s = \frac{A_s}{A} \quad (2)$$

in which A_s = effective cross-sectional area for each pile and A = area influenced by each pile. The magnitude of A depends on the layout of the piles. For example, it may be determined as $A = \sqrt{3} x^2 / 2$ and $A = x^2$ respectively for triangular and square patterns as shown in Fig. 5 in which x is the horizontal distance between the center of one pile to that of an adjacent pile.

The compaction effect is usually evaluated by estimating the increase in density or the increase in N -values. The N -value is regarded as a more reliable indicator than relative density to evaluate the densification effect achieved with compaction piles.

Review of Existing Studies

Some simplified methods have been adopted to evaluate the improvement effect of compaction piles in sandy soil deposits. The most common way is the comparison between the pre- and post-compaction N -values which are obtained directly from field investigation. In addition, several empirical correlations, which incorporate

the replacement ratio and the N -values before and after improvement, have been proposed, such as those by Ogawa and Ishido (1965) and by Mizuno, Suematsu and Okuyama (1987). In the methods by Ogawa et al. and by Mizuno et al., particularly, the influence of fines content on the compaction effect was considered to a certain degree. Figure 6 shows the correlation between post-compaction N -values and fines content for different values of replacement ratio (Mizuno et al., 1987). There seem to exist however the following limitations in the existing studies stated above.

- 1) The existing methods are suitable only for evaluating the densification effect achieved with sand compaction piles. It is not clear however whether or not they may be used to estimate the compaction effect obtained with other types of piles, such as quicklime compaction piles, gravel compaction piles, and pile driving.
- 2) It is well known that the relation between N -value and relative density is significantly influenced by the effective confining pressure (Tokimatsu and Yoshimi, 1983). The effect of effective confining pressure however has not been considered in the existing methods.
- 3) Most data used to consider the influence of fines content such as those shown in Fig. 6, show a large scatter. It is difficult therefore to use it in a practical design with a sufficient level of accuracy. Based on the field test data shown in Fig. 2 and the method by Mizuno et al. (1987), a comparison in Fig. 7 is made between the measured and estimated post-compaction N -values. This figure shows an overestimation when the fines content F_c is more than 20%, and underestimation for $F_c < 15\%$. Consequently, the measured N -values are in the wide range from 5 to 40, whereas the estimated N -values range from 10 to 25.
- 4) The fundamental relationship of Eq. (1), used in the

Fig. 6. Influence of fines content on N -value after compaction (modified after Mizuno, Suematsu and Okuyama, 1987)

Fig. 7. Comparison between observed N -values after improvement and those estimated using the method proposed by Mizuno et al.

existing methods, assumes that the change in void ratio achieved with compaction piling depends only on the magnitude of the volume replaced by the piles. The assumption is not completely true because the ground surface may tend to rise slightly during compaction. The ground surface swelling can reduce the increase in density, depending mainly on the fines content.

5) Field studies show that the N -value after compaction increases adjacent to the piles. This indicates that the density increase is not uniform at a given depth. In general, the measured penetration resistance at the midpoint between the piles represents the minimum value. Such non-uniform densification has not been considered in the existing methods.

SELECTION OF INDICES EVALUATING COMPACTION EFFECT

Factors Affecting Compaction Effect

As seen from this discussion, there are various factors influencing the final densities obtained with compaction piles. They are mainly: 1) initial soil conditions including grain size distribution ($e_{\max}$, $e_{\min}$, D_{60} and U_c), initial density (void ratio e_o and relative density D_{ro}), and fines content (F_c), 2) effective overburden pressure (σ'_{vo}), 3) replacement ratio (a_s), 4) ground surface swelling, 5) non-uniform densification, and 6) vibro-densification effect.

Selection of Indices Evaluating Compaction Effect

In the same way as the existing methods, the N -values before and after improvement were used as the main parameters for evaluating the compaction effect in this study. The following indices will however be introduced to further consider the influence of factors from 2) to 6)

above.

1) *Normalized N -value, N_1* : Considering that the N -values are influenced by the effective confining pressure in the soil deposit, they are normalized for effective overburden pressure, σ'_{vo} , in kPa. The normalized N -value, N_1 , may be approximately obtained from the following relationship (Tokimatsu and Yoshimi, 1983).

$$N_1 = \frac{1.7}{0.7 + 0.01 \times \sigma'_{vo}} N. \quad (3)$$

In addition, based on the normalized N -value, the relative density may be estimated by the following equation (Tokimatsu and Yoshimi, 1983):

$$D_r = 16 \sqrt{N_1 + \Delta N_f} = 16 \sqrt{N_a} \quad (4)$$

in which ΔN_f is a correction term for considering the effect of fines content, and N_a is called adjusted N -value. Tokimatsu and Yoshimi suggest that ΔN_f -value is taken as 0 for $F_c = 0$, $0.1F_c + 4$ for $F_c > 10\%$, and interpolated for $0 < F_c < 10\%$.

In Fig. 8 a comparison between fines content, F_c , and N -value after improvement, N' , at replacement ratio a_s of 0.096 is shown based on the data presented in Fig. 2. For comparison, an average line shown in Fig. 6 for $a_s = 0.05 - 0.125$ was plotted in Fig. 8. The post-compaction N -value, N' , decreases with an increase in fines content. Higher post-compaction N -values were however seen in the soil improvements performed by the authors in comparison with previous results. One of the reasons resulting in the difference of post-compaction N -values probably relates to the difference in actual in situ effective confining pressures between two cases stated above. Replacing N' by N'_1 in Fig. 8 gives the N'_1 - F_c relationship in Fig. 9. Figure 9 shows that the results of the two cases are approximately consistent with each other for $F_c > 15\%$. As a result, the effective overburden pressures corresponding to the data shown in Fig. 6 were probably smaller, about 1 kgf/cm². Comparing the data in Figs. 8

Fig. 8. Influence of fines content on N -value after compaction

Fig. 9. Influence of fines content on normalized N -value after compaction

and 9, the normalized N -values N'_i can be seen to be smaller than the corresponding values of N' . This is because the depths of the improved soil deposits in this investigation were deeper, from 10 m to 25 m as shown in Fig. 2. In addition, the N'_i - F_c relationship shows a significantly smaller scatter than the N' - F_c relationship. This suggests that the normalized N -value is a more reasonable index than N -value for estimating the compaction effect.

Fig. 10. Relationship between relative increase in normalized N -value and normalized N -value before improvement

Figure 10 shows the relationship between the relative increase in normalized N -value after improvement, $\Delta N_i / N_i$, and normalized N -value before improvement, N_i . $\Delta N_i / N_i$ decreases as N_i increases, and in addition, a good correlation exists between $\Delta N_i / N_i$ and N_i over a wide range in fines content from 10% to 70%.

2) *Correction coefficient considering ground surface swelling, α* : Because the ground level tends to rise when piles are penetrated into the soils, the correction coefficient, α , which is defined as

$$\alpha = \frac{\Delta e_{\text{swel.}} (\text{increase in void ratio due to ground surface swelling})}{\Delta e (\text{decrease in void ratio due to compaction by piles})} \quad (5)$$

is suggested to reflect the influence of the ground surface swelling on the density change. Figure 11 shows the correlation between the correction coefficient, α , and the fines content, F_c , measured in several field investigations. The correction coefficient is seen to increase with increasing fines content of the soil. The data indicating the α - F_c relationship show a significant scatter. This is partly because the values of $\Delta e_{\text{swel.}}$ and Δe were determined according to the averaged ground surface swelling and the total volume replaced by piles, respectively. Consequently, the non-uniform distributions of α and F_c with depth were not considered. It is also because α -values were likely to be influenced by other factors than fines content.

If the correction coefficient α is assumed to be zero at $F_c=0$, the α - F_c relationship shown in Fig. 11 may be obtained approximately as follows on the basis of the method of least squares.

$$\alpha = 0.00158 \times F_c^{1.389} \quad (6)$$

3) *Correction coefficient considering non-uniform densification, β* : The density increase in the soil surrounding a compaction pile is generally non-uniform at a given

depth because the resulting post-compaction density increase always decreases as the horizontal distance from the pile center increases. The penetration resistance at the midpoint between the piles therefore, which represents the minimum value, is usually adopted, thereby adding conservatism to the evaluation of compaction effect. In

Fig. 11. Relationship between correction coefficient considering ground surface swelling and fines content

order to consider the non-uniform densification, the correction coefficient, β , is introduced, which is defined as

$$\beta = \frac{e_o - e'_o}{(e_o - e'_o)_{\text{average}}} \quad (7)$$

in which $(e_o - e'_o)$ is the increase in void ratio after compaction at the midpoint between the piles and $(e_o - e'_o)_{\text{average}}$ is the average increase in void ratio. Obviously, $0 \leq \beta < 1$. The condition of $\beta = 0$ indicates that the compaction effect is zero at the midpoint between the piles, whereas $\beta = 1$ is actually impossible because this condition requires that $(e_o - e'_o)$ is equal to $(e_o - e'_o)_{\text{average}}$.

It is worthy of note, that the change in void ratio after compaction can be induced not only by an increase in solid volume, but also by ground surface swelling. The average increase in void ratio $(e_o - e'_o)_{\text{average}}$ is therefore actually the difference between Δe and $\Delta e_{\text{swel.}}$ in Eq. (5) or $(e_o - e'_o)_{\text{average}} = \Delta e - \Delta e_{\text{swel.}}$. The relative increase in void ratio after compaction at the midpoint between the piles can therefore be written as

$$\frac{e_o - e'_o}{1 + e_o} = \beta \left(\frac{\Delta e - \Delta e_{\text{swel.}}}{1 + e_o} \right) = \beta \times a_s \times (1 - \alpha) \quad (8)$$

Figure 12 shows the relationship between the correction coefficient β and the normalized N -value before compaction N_1 at a project site. The β -values were determined using Eq. (8). Based on the same data, the relation-

Fig. 12. Weak dependence of correction coefficient considering non-uniform densification on normalized N -value before improvement

Fig. 13. Influence of fines content on correction coefficient considering non-uniform densification

Fig. 14. Relationship between correction coefficient considering non-uniform densification and replacement ratio

ship between the correction coefficient β and fines content F_c is also shown in Fig. 13. The data points in Figs. 12 and 13 show significant scatter because too many assumptions were included in the formulae for determining β . It may still be stated however that the correction coefficient β is not greatly influenced by N_1 or F_c . This implies that β is a parameter relatively insensitive to soil strength and type of soil.

Figure 14 shows the relationship between the average correction coefficient β_{average} and the replacement ratio a_s obtained at six project sites. As can be seen from this figure, β_{average} increases as a_s increases. Particularly, $\beta_{\text{average}} = 0.6$ at $a_s = 0.1$, which agrees well with the averaged β -values shown in Figs. 12 and 13. Obviously, $\beta_{\text{average}} = 0$ at $a_s = 0$. The $\beta_{\text{average}}-a_s$ relationship may be estimated approximately by

$$\beta_{\text{average}} = 2.93 \times a_s^{0.695} \quad (9)$$

4) *Effective cross sectional area of pile, A_s* : When the replacement ratio a_s is determined by Eq. (2), the effective cross sectional area of the pile may be defined by

$$A_s = C_1 A_{\text{design}} \quad (10)$$

In which A_{design} = average design area of the pile and C_1 = correction coefficient considering the influence of type of pile. The C_1 -value may be taken as 1.0 for sand compaction piles and normal pile driving, and 1.1–1.5 for quicklime piles (e.g., Watanabe et al., 1971; Ishida, 1974).

SIMPLIFIED METHOD FOR ESTIMATING COMPACTION EFFECT

From Fig. 10 it can be seen that a good correlation exists between $\Delta N_1/N_1$ and N_1 over a wide range of fines content from 10% to 70%. Based on this experimental fact, the compaction effect is judged by comparing the normalized N -values before and after improvement using the present method. The normalized N -value after improvement may be estimated approximately by Eqs. (4) and (8) as well as the definition of relative density, namely

$$\begin{aligned}
 N_a &= N_1 + \Delta N_f \\
 D_r &= 16 \sqrt{N_a} \\
 e_o &= e_{\max} - (e_{\max} - e_{\min}) \times D_{ro} \\
 e'_o &= e_o - \beta \times a_s \times (1 - \alpha)(1 + e_o) \\
 D'_{ro} &= (e_{\max} - e'_o) / (e_{\max} - e_{\min}) \\
 N'_a &= (D'_{ro} / 16)^2 \\
 N'_1 &= N'_a - \Delta N_f
 \end{aligned} \quad (11)$$

in which D_{ro} =initial relative density, D'_{ro} =final relative density, e_o and e'_o =pre- and post-compaction void ratio, $e_{\max}$ and $e_{\min}$ =maximum and minimum void ratio. The values of $e_{\max}$ and $e_{\min}$ can be determined approximately by the following empirical relationship as a function of fines content (Hirama, 1981 and Mizuno, et al., 1987).

$$\begin{aligned}
 e_{\max} &= 0.02 \times F_c + 1.0 \\
 e_{\min} &= 0.008 \times F_c + 0.6
 \end{aligned} \quad (12)$$

Based on Eqs. (11) and (12), the relationships between $\Delta N_1/N_1$ and N_1 at $F_c=10\%$, 20% and 40% and $\beta=1.0$, 0.5 and 0.3 for the case of $a_s=0.1$ were calculated and then shown in Fig. 15. This figure indicates that $\Delta N_1/N_1$ decreases noticeably as F_c increases. The degree of the influence of F_c on $\Delta N_1/N_1$ is however significantly smaller than those of the correction coefficient β and normalized N -value before improvement N_1 . This result explains why a good correlation exists between $\Delta N_1/N_1$ and N_1 over a wide fines content range as shown in Fig. 10. By comparing Figs. 10 and 15, it was found that the calculated and measured relationships between $\Delta N_1/N_1$ and N_1 indicate the same trend. This means that the correction coefficient β is not markedly influenced by the difference in fines content. Based on the data for $a_s \approx 0.1$

Fig. 15. Influence of fines content F_c and correction coefficient β on relative increase of normalized N -value with respect to its value before improvement

Fig. 16. A chart for estimating increase in adjusted N -value due to compaction based on fines content, replacement ratio, and adjusted N -value before improvement

shown in Fig. 10, the correction coefficient β was estimated with the method of least squares, and consequently, the β -value corresponding to the least variance in error was 0.62.

The relationships, defined by Eqs. (2), (3), (6), (9), (10), and (11) may be used not only in the actual design of compaction piles, but also in the estimation of compaction effect for a specific design. Figure 16 provides a practical chart for the empirical correlations between increase in adjusted N -value, ΔN_a , and pre-compaction adjusted N -value, N_a , at fines content $F_c=10\%$, 20% , and 40% and replacement ratio $a_s=0.05$, 0.1 , and 0.15 .

A convenient way to estimate the compaction effect is to calculate the increase in N -values or density increase by using the empirical relationships described above or shown in Fig. 16.

VALIDITY OF PROPOSED PROCEDURES

In order to confirm the effectiveness of the method of evaluation proposed above, an estimate of the increase in normalized N -value after compaction was made for the site shown in Fig. 2. Figure 17 indicates good agreement between the estimated and measured normalized N -values after compaction. This suggests that the proposed methodology can be used for evaluating the improvement effect achieved with compaction piles.

Fig. 17. Comparison between observed normalized N -values after improvement and those estimated by the proposed method

CONCLUSIONS

A simplified method has been proposed to estimate the improvement effect achieved with various compaction piles for sandy soils containing fines. The main factors affecting the compaction effect are 1) initial soil conditions such as initial density and fines content, 2) effective overburden pressure, 3) replacement ratio, 4) ground surface swelling, and 5) non-uniform densification. Based on the analysis of extensive field data and previous studies, several empirical relationships incorporating the main factors stated above were established in this study. By using this method, the improvement effect can be evaluated by comparing the normalized N -values before and after improvement. The estimated results have been compared favorably with those obtained from actual field investigations. The proposed method may be adopted in the actual design of sand compaction piles. It may also be expected to be used for other compaction piles such as quicklime piles.

It should be pointed out that post-compaction densities can also be influenced by other factors, such as back-fill materials, restrictions of construction site and space,

availability of equipment, skill of operators, and quality of supervision. These factors have not been considered in evaluating this method. It is necessary to check the estimated results by the proposed method based on available experience.

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