L'UTILISATION DES PIEUX DE SABLE POUR L'AMELIORATION DES SOLS MOUS : UNE REVUE

THE USE OF SAND COMPACTION PILES IN IMPROVEMENT OF SOFT SOIL: A REVIEW

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Résumé - Ce que l'on sait des sols mous, ce sont les nombreux problèmes résultant de la construction sur ce type de sol, tels que leur faible capacité portante, leur faible résistance aux forces de cisaillement, leur tassement élevé (sol compressible) et leur faible résistance aux forces horizontales. Pour ces problèmes, la méthode des pieux de sable (SCP) a été utilisée et des méthodes ont été identifiées pour assurer l'amélioration de la faiblesse rencontrée dans les sols mous. Cette recherche ne traitera pas de toutes les méthodes de calcul des pieux de sable, mais présentera les recherches fondamentales adoptées dans les méthodes de conception en sols argileux et sableux, ainsi que le calcul de la capacité portante, du tassement dans les deux types de pieux de sable (fixes ou flottants), la stabilité des sols composites (SCP et argile et, à la fin de la recherche, nous présentons quelques applications de pieux de sable en grandeur nature et en modèle réduit, en mentionnant les avantages et les inconvénients de cette méthode.

Mots - clés : Pieux de sable, Capacité portante, Tassement, Sols mous, Renforcement.

Abstract - What is known about soft soils are the many problems resulting from building on them or operating them, such as their low bearing capacity, low resistance to shear forces, high settlement (compressible soil), and low resistance to horizontal forces. For such problems, the sand compaction piles (SCP) method was used, and paths were identified to ensure the improvement of the weakness encountered in soft soils. This research paper will not deal with all methods of calculation of sand compaction piles, but will present the fundamental research adopted in the design methods in clay and sandy soils, and so on the calculation of bearing capacity, settlement in the two types of sand compaction piles (fixed or floating), the stability of composite soils (SCP and clay), and at the end of the research, we will present some applications of Sand compaction Piles in reality and in scale models, mentioning the advantages and disadvantages of this method.

Keywords: Sand compaction piles, Bearing capacity, Settlement, Soft soil, Reinforcement.

1-Introduction

Sand compaction piles (or compacted sand piles or sand piles) are a long-term method of improving soft soils. This method has proven itself, especially in Japan, due to its widespread use there. Like any method of improvement, there are methods for designing sand piles that must be followed to ensure that the desired results are obtained from the experiments of the first scientists in this field.

The purpose of this research is to give an overview of the routes taken to build sand compaction piles, as well as to cite some examples and show the advantages and disadvantages of this method.

Mirayama is considered the first theorist of the sand compaction pile method (1957) (1958) [1 & 2], and he developed his theories over several years, he published his first paper on sand compaction piles in clay soil in 1962 [3], followed by Tanimoto [4] and Aboshi et al [5] and Jung et al (1999) [6] and others to make d other advances.

These are some of the theorists of the sand compaction pile method, basing their research on basic geotechnical theories (such as Terzaghi, Skempton, and others), and those who have come recently have developed this than their predecessors did, and they achieved control over bearing capacity, consolidation, construction issues and design methods.

The design methods are divided into the division of soft soils, there are design methods in sandy soils which depend on densification, and there are design methods in clay soils which depend on the concentration of forces [7]. What we will focus on in this research is design methods in clay soils, which themselves are treated in two ways: the first by consolidation settlement and the second by studying the stability of the improved ground.

In this research, we were first exposed to the inputs of design methods in clay and sandy soils, then we focused the rest of the research on clarifying bearing capacity formulas, studying the stability and the behavior of settlement in clay soil, with real examples mentioned in the latter, accompanied by the advantages and disadvantages of this technology.

2- Design methods

The principle of the method for the design of sand compaction piles is (illustrated in figure 3):

- *for soft clay soils: the replacement surface ratio is the major principle for improving offshore structures, and the stress concentration ratio for onshore structure [3].*
- *for sandy soil: reduce the void index and densify the soil [8].*

Improving clay soils divided into a square, equilateral triangular or rectangular pattern, as shown in Figure 1.

The ratio of the pile area to the reinforced soil area is represented by the replacement area ratio:

$$as = \frac{As}{A} \quad (1)$$

Where: as: is the replacement area ratio, As: sectional area of sand pile, A: cross sectional area of original ground and sand pile.

The area replacement ratio for applications to sandy ground is typically less than 0.3, and for clay ground the ratio ranges from 0.3 to 0.8. In case of the area replacement ratio of about 0.78 sand piles are in contact with each other. The SCP improved ground can be divided based on area replacement which is given in Table 2.1 [9].

Table 1: Classification of SCP Imporved Ground based on Area Replacement [9].

Types of improved ground	Area replacement (%)
Low area replaced ground	0 to 30
Medium area replaced ground	30 to 50
High area replaced ground	> 50

The SCP method can be considered to be a composite ground (SCP+clay), the concentration of forces on compacted sand piles is not equal to the concentration of forces on clay (not the same characteristics), which is defined by the stress concentration ratio:

$$n = \frac{\sigma s}{\sigma c} \quad (2)$$

Where: n: stress concentration ratio, σs: vertical stress on sand pile, σc: vertical stress on clay ground.

Note that the formulas for σs and σc are in terms of as.

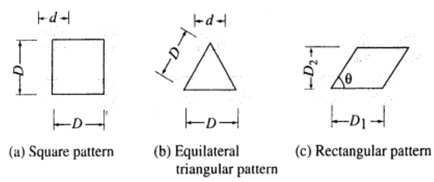

Figure 1. Soft clay soil improvement model [7].

The spacing between sand compaction piles in sandy soil can be determined by in four different ways, all based on the SPT test [10], which gives void ratio, relative density and count (N-SPT), We will mention one of the methods Equation (3), and one can refer to the references to see the other methods, using the pile diameter 70 cm and the replacement area ratio (see figure 2) :

$$as = \frac{(e0-e1)}{(1+e0)} \qquad (3)$$

$A = x^2 = \frac{As}{as}$ for square arrangement

$A = \frac{\sqrt{3}}{2} x^2 = \frac{As}{as}$ for regular triangular arrangement

Where: e0: initial void index, e1: final void index, x: spacing.

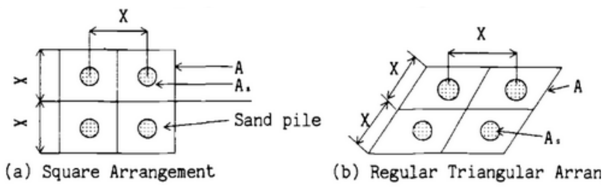

Figure 2. Spacing of SCPs in sandy soil [17].

Note that the initial and final void index are calculated from the relative density, and the relative density is calculated from the SPT test.

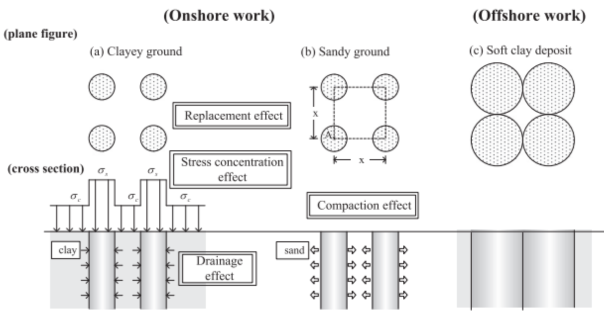

Figure 3. Concept for installation of compacted sand piles [11].

3- Bearing capacity of SCP

We will discuss here the methods of calculation of the bearing capacity specify for the piles of sand, as for the current methods (like Meyerhof, Terzaghi …) like the calculation by the test SPT [12], Pressuremeter test … it is not necessary to mention them here because they are general theories and not specific to sand compaction piles.

3.1- Bearing capacity in the event of the consolidation settlement

The distinction between the calculation of the bearing capacity in the sand compaction piles individually or in groups is by the ratio as, in the case of the replacement area ratio of about 0.78, the sand compaction piles are in contact with each other the others (so they are considered a group) [7].

The formulas for calculating the bearing capacity in sand piles are mostly the formulas of the composite ground, such as the formula of Greenwood (1970) [13], Hughes and Withers (1974) [14], Wong (1975) [15] and others. This is due to the scarcity of formulas specific to sand compaction piles.

The formulas for calculating bearing capacity that will be presented in this paper are the formulas found in recommendations in Japan.

Bearing capacity of single sand piles:

The principle of its calculation is that the sand compaction piles and the surrounding clay are subjected to equal vertical settlement, leading to a stress concentration on the sand compaction piles, Murayama came up with a formula for calculating bearing capacity in Equation (4) mainly based on the unit cell approach (composite soil):

$$P = \sigma u \frac{1+\sin\phi s}{(n-1)+(n+1)\sin\phi s}(As.n + A) \qquad (4)$$

Where: P: bearing capacity, σu: upper yield stress of clay ground, ϕs: internal friction angle of sand pile.

This formula was written by Murayama based on the equations below:

- *The vertical stress:* $P = \sigma c .(As . n + Ac)$
- *The horizontal stress:* $\sigma h = \frac{1-\sin\phi s}{1+\sin\phi s} .\sigma s$

$$\sigma h \leqq \sigma c + \sigma u$$

- *The stress concentration ratio n (it is given empirically or calculated by experiments [16])*

Bearing capacity of improved soil with multiple sand piles:

The bearing capacity of SCP-improved soil (as a group) is often evaluated by Terzaghi's bearing capacity theory as shown in equation (Equation (5) and (6)) (and figure 4) or slip circle analysis.

Terzaghi method:

$$P = qa \cdot A \quad (5)$$

$$P = \{as \cdot qas + (1 - as) \cdot qac\} \cdot A \quad (6)$$

With qac it is the bearing capacity of clay:

$$qac = c \cdot Nc \cdot \frac{1}{Fs} \quad (7)$$

And qas is the bearing capacity of the sand compaction pile:

$$qas = \left(\frac{1}{2}\right) B \cdot \Upsilon s \cdot N_{\Upsilon} \cdot \frac{1}{Fs} \quad (8)$$

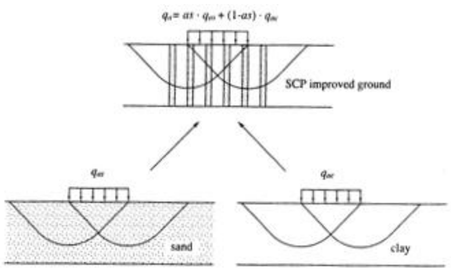

Figure 4. Bearing capacity calculation by Terzaghi's theory [7].

3.2- Stability of improved ground

Bearing capacity of improved soil with multiple sand piles:

Slip circle analysis method (illustrated in figure 5):

$$P = \frac{1}{Fs} \cdot \frac{R \cdot \Sigma(\tau \cdot \Delta l)}{x} \quad (9)$$

Where: P: bearing capacity, R: radius of slip circle, τ: shear strength of improved ground, Δl: arc of slip circle, Fs: safety factor, x: horizontal distance of weight of embankment or external load measured from center of slip circle.

$$Fs = \frac{MR}{MD} \quad (10)$$

Where: M_D: driving moment, M_R: resisting moment.

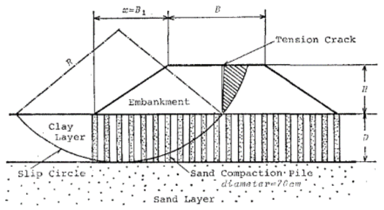

Figure 5. Slip circle analysis for bearing capacity (example of embankment) [18].

There are many who have proposed equations to calculate the shear strength of composite ground in general and for sand compaction piles in particular, as an example, we have the Murayama [3], Tamura (1974) [19] and Aboshi et al. (1979) [20] equations.

4- Settlement of SCP

There are two types of sand compaction piles, fixed and floating, and each of them has settlement calculation method, the difference between them is that the floating type depends on the formula of the SCP fixed type and then adds the settlement of the layers between the SCPs, the details can be found in the sections below.

The basic formulas used to calculate settlement assume that the composite ground (SCP + soft soil) deforms under one-dimensional confined compression, and this is the same general assumption used to calculate settlement.

There are many other studies that have developed equations to calculate settlement in composite ground such as Greenwood (1975) [21], Aboshi et al. (1979) [20], Priebe (1976) for stone columns [22] and others. What will be shown is based on Japanese recommendations.

4.1- Settlement of fixed SCP

Settlement calculation is with below formula, where: S: settlement of improved ground, S_0: settlement of unimproved ground, β: settlement reduction factor.

$$S = \beta \cdot S_0 \qquad (11)$$

$$\text{And } \beta = \frac{1}{1+(n-1).as} \qquad (12)$$

The coefficient β we can calculate it through the formula or through the empirical graphs (example: figure 6).

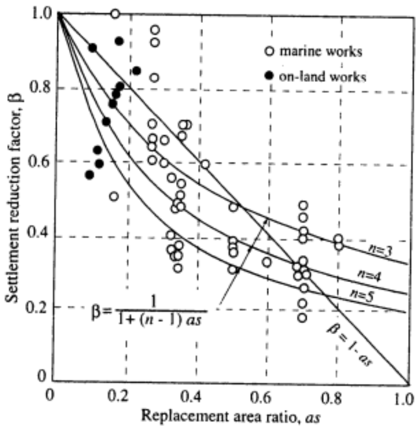

Figure 6. Relationship between replacement area ratio and settlement reduction factor [7].

The settlement S_0 is calculated from Terzaghi's theorem:

$$S0 = H \cdot Cc \cdot log\frac{\sigma}{\sigma 0} \qquad (13)$$

Where**:** H: ground thickness, Cc: compressive coefficient of ground, σ: vertical stress, $\sigma 0$: initial vertical stress.

4.1- Settlement of floating SCP

The design of this case is shown in figure 7.

$$S = St + Su \qquad (14)$$

$$= \beta \cdot S_0 + Su \qquad (15)$$

Where: S: settlement of SCP improved ground, St: settlement of SCP improved layer, Su: settlement of unimproved layer underlying SCP improved layer.

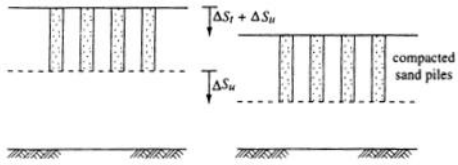

Figure 7. Illustration of settlement of floating type of improved ground [7].

In this type of improvement, SCP-clay interaction is not yet well understood, so quite complicated settlement calculation, settlement calculation in sand compaction piles is as in fixed type, but settlement in the layer of clay, no particular method has been determined for its calculation in the case of improvement with sand compaction piles, which is why they used the distribution of the loads in the deep mixing method of the floating type (illustrated in figure 8).

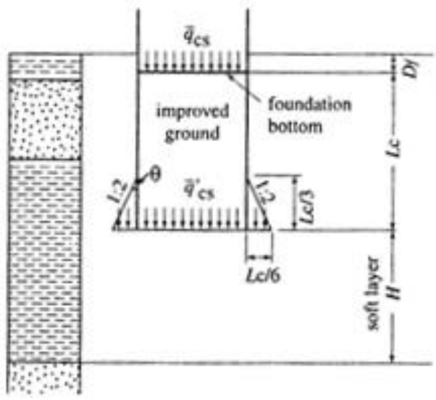

Figure 8. Illustration of stress distribution for floating type Deep Mixing improved ground [7].

the calculation of the resulting ground settlement with floating columns is based upon a stress distribution ratio approach where the stress is distributed over the soil and columns, and settlement is calculated based upon the ratio of stiffness of the soft clay to the stiffness of the columns, assuming uniform strain below the embankment [7 & 23].

Investigation of the floating type composite ground has received relatively limited attention [6, 24, 25].

5- Types of monitoring tests

A number of monitoring tests have been carried out to assess the results of the sand piles, and each of them has its own limitations to check and confirm the correct construction of sand compaction piles, the main tests are [26]: Soil sampling, SPT before and after the installation of SCP, Laboratory relative density tests, Piezometer, Inclinometers, Borehole lateral load tests, Vane shear tests.

6- Case Studies

There are many successful experiences of this method, some of which have been embodied in the field, and some of which have been embodied in the form of a scale model, and even in digital software.

For example, the improvement of a storage tank with sand piles. after the 1978 Miyagiken-oki earthquake, a clear difference appeared between the improved area at the bottom of the reservoir and the adjacent unimproved areas (see figure 9), to prove once again the net effect of this technique (SCP) on the soils soft.

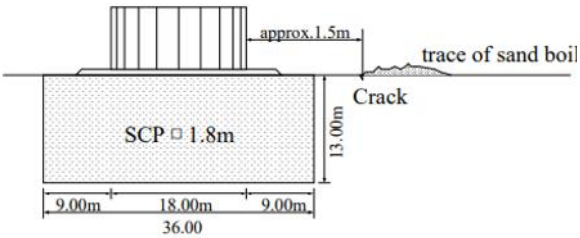

Figure 9. Standard section of storage tank facility [27].

Another case is a river embankment was also improved with sand piles after several problems that happened to it, and it was the first use of sand compaction piles in river embankments, and the results were very positive, because there were no problems in the stability of the river embankments (see figure 10), not only due to the forces and climatic factors, but even during earthquakes, except for slight cracks, it appeared as a result of the cracks that previously appeared before improvement.

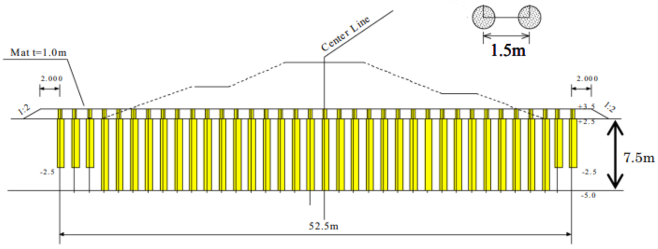

Figure 10. Standard section of river embankment [28].

S.K. Yadav et al. did two centrifugal physical modelling tests were performed on floating and fixed SCPs improved soft clay under embankment loading, the purpose of the experiments was to compare the difference between the fixed and the floating SCPs, and also to see the effect of SCPs in soft clay soil. The results showed the success of the improvement to strengthen the soft soil, with a difference in favor of the fixed piles.

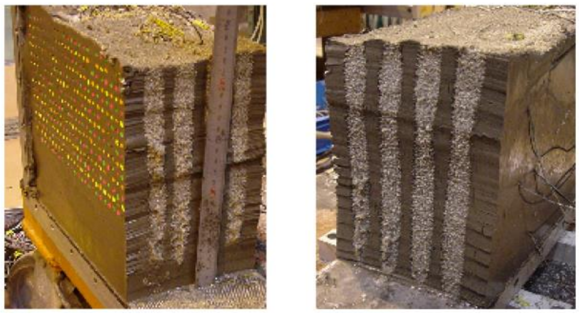

Figure 11. Samples formation for centrifuge physical modelling (floating and fixed SCPs) (S.K. Yadav at al. 2019).

7- Advantages and disadvantages of SCP

The main advantages of sand compaction piles over stone columns are [30]:

- No silty water disposal problem,
- Hole fully supported,
- Used cheap,
- Local sand,
- Very soft soil will not penetrate column,
- Method is very fast,
- Accelerates consolidation settlement.

Sand compaction piles also have several significant disadvantages that must be carefully considered during design. The main disadvantages of sand compacting piles are:

- Smear from advancing casing reduces horizontal permeability,
- Is not dissipated during earthquake,
- Consider local bearing failure in very soft soils,
- More settlement and lower strength than stone column (they have a lower internal friction angle and lower stiffness than stone columns).

8- Conclusions

The paper dealt with the basic formulas of the sand compaction pile method, not all of them, but the most famous ones (Japanese recommendations), it also mentioned several knowledge about sand compaction piles in clay and sandy soils, to finally mention each of the types of monitoring used, realistic examples of the application of this technique, and the advantages and disadvantages of this technique. Such a paper gives you a general view on this subject and opens doors for you to present the addition in its decreasing aspect, especially since it is a technology whose development barrier is still high. Some conclusions, for example: the design method of sand compaction piles changes with the change of soft ground types, the improvement after the occurrence of certain technical problems is not of the same quality as the improvement before their solutions, the great use of this technology in Ports (offshore) shows that it is the best improvement technology in water currently, confirming what has been mentioned that floating SCPs Less quality than fixed SCPs, and more informations.

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