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# Settlement calculation method of rivet pile composite foundation under embankment load[1]

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**Abstract.** The settlement calculation method of rivet pile composite foundation under embankment load is a basic problem often encountered by engineering. Generally, the composite elastic modulus method is used to calculate the settlement of the rivet pile. But in this process, there is still a "mass" role between the rivet piles, and the calculated value is quite different from the actual situation. In this paper, the interaction effect of rivet pile was discussed based on the basic data of existing research and practical measurement. A method of calculating composite foundation with two layers settlement was put forward for a composite foundation of rivet pile. The actual effect of the algorithm was verified by a practical engineering example.

**Key words.** Embankment load, composite foundation, rivet pile, settlement calculation.

## 1. Introduction

In recent years, China's highway infrastructure construction and development has entered a stage of rapid development, especially in the eastern coastal areas with better economic development. The ground base of coastal cities is weak because the area affects the structure of soft soil in this area. But during the construction of expressway, the soil layer structure of soft layer is the inevitable basic problem in engineering construction [1]. During the practice of soft layer treatment, many basic problems of soft soil are found, such as surcharge preloading and reinforcement. Although these design methods have their own advantages, many construction defects are inevitable [2]. The method of preloading can really deal with the insufficient depth of soft soil layer, and the cost of using pure rigid piles is high. This provides

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opportunities for the development of soft soil treatment methods for rivet piles, while the two-way "rivet pile" application is put forward in such a context [3]. For the application of concentrated load rivet pile, there are still few researches on quantitative calculation of consolidation and deformation. Generally, the engineering design of the foundation uses the settlement as the standard foundation. In addition to the necessary bearing capacity of the project, it is necessary to calculate the coincidence between the calculated results of settlement and the actual conditions. This requires the calculation accuracy of the rivet pile composite foundation, so the optimization of the calculation method is imperative [4].

## 2. State of the art

The two-way foundation characteristics of the rivet pile composite foundation under the embankment load determine the cause and effect of settlement calculation, and also limit the coordination relationship between rivet pile and soil [5]. It is necessary to consider the sharing of the rivet pile and the land load under the action of the external load and the carrying capacity of the land. In addition, the problem of larger end of rivet pile needs to be analyzed, which makes the calculation method of composite foundation settlement of rivet pile become complicated. Rivet pile is a new type of composite foundation combined pile. It has high application value in construction of composite foundation. However, the research literature about it is very rare [6]. Some scholars have simulated and analyzed the larger end design capacity of rivet pile. On the basis of the same geological or soil foundation, the ultimate load carrying capacity of rivet pile is larger than that of ordinary pile. Therefore, it is necessary to put forward the calculation of the bearing capacity of rivet pile [7].

For the same soil foundation construction, through the comparison of the load test of rivet pile and conventional pile, it can be seen that the deformation data of composite foundation have big experimental data difference [8]. On the whole, it can be found that the foundation depth of the rivet pile is uniform, and the depth of the conventional pile is inversely proportional to the strong support of the pile. For some application parameters of rivet pile, the conclusion is less, but it is necessary to analyze and discuss some construction parameters [9]. The calculation of bearing capacity of composite foundation with rivet piles needs to be studied deeply. The settlement calculation of composite foundation of rivet pile is not perfect, and the role between rivet piles is not clear [10]. The surface of the soil layer in the eastern coast is hard, and the middle layer is a soft soil layer. It makes it possible to analyze the bearing capacity and settlement characteristics of the lower layer of the hard layer foundation when using rivets to reinforce the composite foundation.

### *2.1. Methodology*

There is a certain pile group effect in the rivet pile under the embankment load. It is found in the literature that there is a mass effect in the enlarged part of the composite foundation settlement of the rivet pile under the embankment load. Some

scholars have designed the method to transfer the load of an independent rivet pile, and calculated the value of the settlement of the foundation. However, the results obtained are not consistent with the actual measured values, which seriously ignore the interaction mechanism between rivet piles. Based on the applicability of the basic research and practical construction, the soft soil structure of the coastal cities in the eastern part of the country needs to be dealt with. The settlement is mostly the composite settlement of pile groups. Therefore, the group effect of rivet pile must be considered in the design of settlement calculation method of composite foundation [11]. In order to study and discuss the regional settlement effect of composite pile foundation with rivet piles, the basic model of composite foundation is set up. The larger end of the element body is enlarged, and the depth of the rivet pile at the lower part is divided into three bearing layers for calculation. The reinforcement layer is solved by compound modulus calculation method. Enlarging the composite modulus of rivet head needs to consider the mass effect of rivet pile, and the lower part of pile cannot be considered. By applying the method of gradual stress diffusion, the applied stress of the underlying lower layer is calculated in advance. The settlement value of composite foundation is calculated by the method of layer synthesis calculation.

In the course of soil bearing capacity of soft soil layer with hard layer, with the increase of load, the internal stress of hard layer is composed of two stages: elastic layer and ultimate elastic layer. It is assumed that the embankment is less than a certain height, and the composite base is in an elastic deformation stage. The hard layer will bear most of the load and transfer the load to the outside of the embankment. In this way, the stress transmitted to the soft soil layer is greatly weakened. In such a state, the compression settlement of the soft soil layer will be relatively small. Although the stress of the hard layer of the soil is relatively large, the rigidity of the hard layer is relatively large. The hard layer capture is compressed too much without exceeding the limit compression capability. Therefore, the overall settlement of the foundation is small and it will soon be restored.

It is assumed that the original elastic working state is broken by the height of the embankment, and the thickness of the plastic change layer increases gradually. Then the rigidity of the hard layer will be weakened, the stress of the soft soil layer will be increased, and the distance of settlement will gradually increase. This is referred to in the literature that when the embankment exceeds a certain height, the settlement value of the hard layer foundation will change qualitatively. In the process of increasing load, the ultimate state of composite foundation will be bigger and bigger. The deformation of the foundation may be very large. The hard and soft layers have been adjusted to the limit, but the hard layer still maintains relatively high shear strength. The strength difference between the hard and soft layers is stress distribution and foundation ratio, and the trend will tend to the upper part of the foundation. The hard layer and the upper soft soil bear the greater load on the composite foundation. The stress of the lower soft soil is small, and the compression of the composite foundation is relatively small. The compressibility of the upper soil determines that the total settlement is less than the foundation without the hard layer structure.

The double deck structure of composite foundation means that in the foundation

construction process, the reinforcing layer and the soft soil layer form the condition of upper firm and lower soft, so as to improve the deformation characteristics of the bearing capacity change. In the treatment of soft soil foundation of expressway, the rivet pile is embedded in soft soil layer, which is a typical strengthening structure. The surface of reinforcing area is hard layer, and the lower layer is soft soil layer structure. The bearing stratum is the soil layer between the two forces. In different soil layer structures, distinct strength and stiffness differences are formed. The strength and stiffness difference of the bearing capacity of the composite foundation is similar to the bearing capacity of some kind of slab. Different laminates form different compression deposition effects. The plate body is more obvious for the diffusion stress of the embankment load, which can effectively weaken the additional embankment stress in the soft soil layer, so that the bearing capacity and settlement characteristics of the composite foundation can be effectively improved.

Through a large number of field tests, it is believed that the deformation of the rivet pile is different from that of the rivet pile under the action of the external load of the rivet pile, and the key problem is the deformation coordination between the rivet piles. Compared with reinforced concrete, the stress and compressive modulus of rivet pile are relatively small. Therefore, after the static loading test, the curve is generally smooth curve. There is no obvious inflection point, and the force is closer to the soil structure, rather than rivet pile. At present, the larger end of the rivet pile is slightly higher than the height of the hard soil layer. The area of the enlarged head is larger than the straight section of the lower part. The composite growth value of the enlarged head is larger than that in the lower part. Under the action of embankment load, the group effect of rivet pile composite foundation is more obvious.

It is assumed that the composite foundation of rivet pile is a composite foundation with double deck. The thickness of the first layer composite foundation is the middle extended depth range. The thickness of the second layer composite foundation is the depth area of the lower pile in the strengthening area, as shown in Fig. 1. The depth change of composite foundation in the first layer is $S_1$, and it is $S_2$ for the second layer and $S_3$ for the third layer. The total settlement of the composite foundation of the last rivet pile is

$$S = S_1 + S_2 + S_3 \,. \tag{1}$$

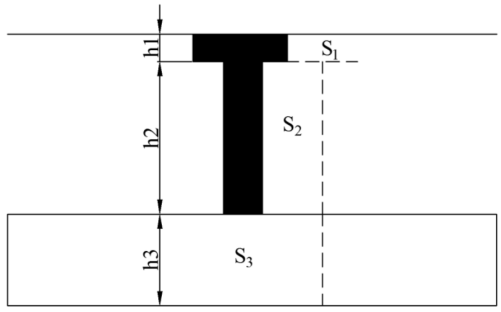


Fig. 1. Calculation model of settlement of rivet pile

The empirical values show that the relationship between 85 % of the actual strength of the rivet piles and the soil properties and soil age parameters is as follows:

$$q_{\mathrm{M}} = \mathrm{e}^{-1.28}(\omega/\omega_{\mathrm{L}})^{-0.819}(C/\omega)^{0.972}t^{0.156}\,. \tag{2}$$

In the above formula , $\omega$ represents the soil water content probability, $\omega_{\mathrm{L}}$ represents the liquid limit ratio of the soil body, $C$ represents the amount of cement used, and $t$ represents the time limit for the use of the cement in the soil. If the number of rivet piles is relatively large, the group effect of rivet pile should be considered. Finally, the group effect of rivet pile is established with the calculation formula

$$E_{\mathrm{SP}} = [\beta_1, \beta_2][E_{\mathrm{p}}, E_{\mathrm{s}}]\,. \tag{3}$$

In formula (3), $\beta_1$ and $\beta_2$ respectively represent the proportion coefficient of rivet pile composite modulus, including the basic factors of influence. Symbols $E_{\mathrm{p}}$ and $E_{\mathrm{s}}$ represent the deformation modulus before and after the deformation of the pile.

Taking the 6 rivet piles as an example, the interaction between adjacent rivet piles takes into account only the relation between the 1# rivet pile and the 2#–5# rivet pile. The distance between the piles outside the rivet pile is so far away that such a long distance can be neglected. For the cube rivet pile, each pile outside has its influence on pile rivet. For a plum shaped rivet pile, there are 6 rivet piles outside each rivet pile, as shown in Fig. 2. Assuming that the influence of the modulus of elasticity between the square rivet piles can be calculated, the calculation method and formula for the rivet pile with plum blossom shape and even more shapes can be deduced.

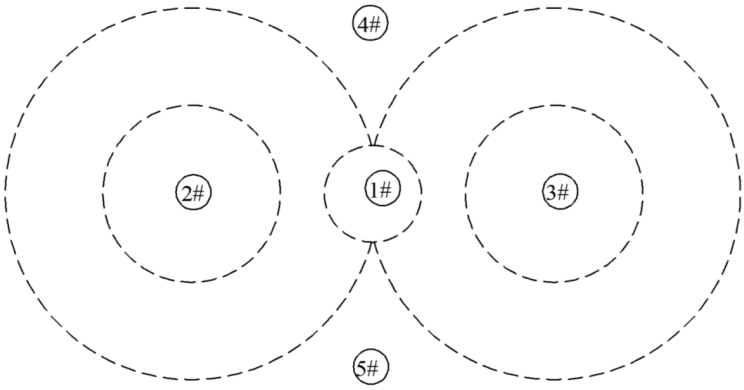


Fig. 2. Influence of pile forming process on soil composite modulus

The expression for the influence between the rivet piles is:

$$E_{\mathrm{sp}} = \beta_1 E_{\mathrm{p}} + \beta_2 E_{\mathrm{s}}\,. \tag{4}$$

Based on the theory of elastic deformation, the composite modulus is solved to calculate the settlement of the reinforcement region.

The depth range of the enlarged part is calculated as

$$s_1 = \frac{(p + p_1)H}{2E_{sp1}} \tag{5}$$

The depth range of the lower part is calculated as:

$$s_2 = \frac{(p_1 + p_2)L}{2E_{\mathrm{sp2}}}\,. \tag{6}$$

In the formula, $p$ represents the load on the surface of the rivet pile composite foundation (kPa), $p_1$ represents the equivalent applied stress on the top of the enlarged part of the rivet pile (kPa), $p_2$ represents the equivalent additional stress under the rivet pile composite foundation (kPa), $H$ represents the height of the enlarged head of the rivet pile (m), $L$ represents the height of the pile at the lower part of the rivet pile (m), $E_{\mathrm{sp1}}$ represents the composite modulus at the upper depth of the composite foundation of the rivet pile (MPa), and $E_{\mathrm{sp2}}$ represents the composite modulus at the lower depth of the composite foundation of the rivet pile (MPa).

According to the design codes' requirements of building foundation, the depth deformation degree of building foundation is calculated as

$$\Delta s'_n \leq 0.025 \sum_{i=1}^{n} \Delta s'_i\,, \tag{7}$$

where, $\Delta s'_i$ represents the calculated soil depth of the $i$th layer within the calculated depth range, $\Delta s'_n$ represents the calculated soil depth for the thickness $\Delta z$ within the calculated depth range.

Assuming that the adjacent load of the rivet pile is affected, and the design range of the foundation is from 1 m to 30 m, the calculation formula of the foundation deformation depth is:

$$Z_n = b(2.5 - 0.4 \ln b)\,. \tag{8}$$

The concept of "$b$" described in formula (8) is the base width, and the unit is m. The depth of settlement of composite foundation is calculated according to the above formula. When there is a soft soil layer, it should continue to be calculated downward until the experimental results in the soft soil meet the required position.

## 3. Result analysis and discussion

The highway test area of a high speed section is used as the object of study. The experimentation area is located in soft soil areas, and the surface width of the embankment is about 34 m. The height of embankment after filling is about 5.8 m, and the ratio of slope to angle is about 1:1.4. The width of the embankment surface is about 52 m, and the lower water level is flush with the surface of the ground, as shown in Fig. 3.

In the structure of soil layer, the main physical and mechanical indexes are shown

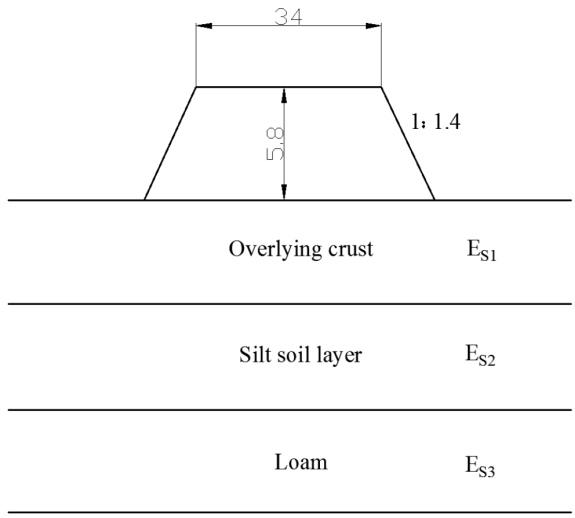


Fig. 3. Embankment profile

in Table 1.

Table 1. The main physical and mechanical indexes of soil layer structure

| i | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Layer | Embankment fill | Hard layer | Silt layer | Loam | Bearing stratum |
| Height m) | 6 | 2 | 13 | 2 | 48.5 |
| $r$ (kN/m$^3$) | 20 | 19.3 | 17.5 | 19.5 | 20 |
| $E_{si}$ (MPa) | 20.4 | 11.7 | 2.8 | 13.2 | 20.4 |

The area in which the experimental area is located is the plain area of a lake. The surface is medium compressed soft plastic sub clay with the thickness of 4 m and the settlement is the silty clay with the thickness of 14 m. The water content of the soil layer is about 50 %. The natural average land porosity ratio in the lake is about 1.42, and the bearing layer is sub clay. The project is located in a high speed section of Jiangsu and Zhejiang, and the rivet pile used is "K30+140". In the experimental stage, composite foundation of rivet pile is used to soften foundation. The length of the designed rivet pile is about 16 m, and the diameter of the rivet pile is about 500 mm. The upper height is about 4 m, and the lower height is about 12 m. The spacing of rivet piles is 2 m, and the distribution rule is plum blossom shape. The severe value of rivet pile is 21 kN/m$^3$. In this experiment, the change of the modulus of rivet pile with the soil layer is only considered, so the compression modulus is 83.3 MPa.

In order to verify the practicability of the settlement calculation of composite foundation in this paper, the author considers that the method of simulation and composite modulus can be adopted. The design concept of double layer composite

foundation is put forward. The research object of this paper is the standardized calculation of composite foundation settlement. Various calculations are shown in Table 2. The calculation method and measured results of the calculation examples are given in Table 2. Through the comparative analysis, the calculation method of composite modulus ignores the group effect of the hard soil layer, and the interchange function of the rivet pile is relatively exaggerated, so that the settlement value of the calculated reinforcement area is too small. The simulation results are close to the actual measured values. However, for the general engineering and technical personnel, it is difficult to master this method in a short period of time. The settlement calculation method of double layered composite foundation is easy to understand and feasible in practice. The design parameters of the rivet pile are considered at the same time. The settlement value is too large, but it is also within the design error range.

Table 1. The results of various methods of calculation

| Number | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Computing method | Complex modulus method | Research methods in this paper | FLAC3D | Measured settlement value |
| Calculation result (mm) | 264.4 | 318.3 | 285 | 281 |

## 4. Conclusion

In practical engineering practice, the settlement calculation of rivet pile composite foundation is widely used. Based on the existing research results and measured data, the group effect of rivet pile composite foundation was analyzed in this paper. A double-layer composite foundation method was put forward for settlement calculation of double-layer structure of rivet pile composite foundation reinforcement. The results were verified by a practical case analysis and satisfactory results were obtained. Based on the study of the settlement calculation method of composite foundation with rivets, the group effects of the hard layer and soft soil foundation were taken into account. A model of double-layer composite foundation strengthened with rivet pile composite foundation was put forward, and the settlement value of composite foundation was calculated. Calculation method of ground settlement was induced by double-layer composite foundation model. The experimental results show that the double layered composite foundation can be combined with the method of rivet pile reinforcement to calculate the ground drop value. The double-layer composite foundation settlement calculation model was used to determine the calculation parameters of the settlement of pile composite foundation such as deformation modulus of rivet pile, the pile body range of upper and lower enlarged part, thickness and calculated depth of the deformation layer. The calculation methods of settlement of composite foundation with various rivet piles were analyzed. By comparing the results of the double-layer riveted pile composite foundation proposed in

this paper, it is proved that the group effect of rivet pile is scientific and effective.

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