Study on Deformation Analyzing Method for Composite Foundation with Lateral Restriction

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Abstract: To limit the lateral and compression deformation of soft soil within the scope of embankment loading, and effectively control embankment settlement, a new technique of ground treatment and a new analyzing method for settlement were proposed in this paper, respectively. Based on displacement variational method, an approximate analytical algorithm for deformation of the composite foundation proposed in this paper under embankment load was established, and approximate analytical formula of the relationship between load and average settlement of the composite foundation was deduced. To verify the feasibility of proposed method, model test of the composite foundation with rammed soil-cement piles and lateral restriction was performed in laboratory, and the proposed method in this paper was used to analyze this model, the results are consistent with the measured results.
Keywords: relationship between load and settlement; displacement variational method; embankment loading; composite foundation

1. Introduction

Now, one-dimensional settlement calculation method is often used to calculate embankment settlement. The assumptions of one-dimensional settlement calculation method are that, soil is elastic, stress distributing of soil accords with Boussinesq solution, soil has not lateral deformation and it has vertical compress merely. The former research results indicate that, if the thickness of compressed soil is much smaller than the area of loading distributing, the aforesaid assumptions are tenable on the whole[1,2]. For soft ground, the lateral deformation of soil affects ground settlement very remarkably, and the lateral displacement of soil changes with level distance from embankment center, the bigger lateral displacement is often underside of embankment shoulder[3]. Factors of affecting lateral displacement contain soft soil properities and height of embankment, et al. If soil is softer, soil is thicker, embankment is higher, then, the lateral displacement and its correspongding settlement are bigger. In this instance, the calculation results of settlement ignoring influence of lateral deformation is on the low side[3]. The research of influence of soil lateral displacement on ground settlement has not been interrupted yet. Tu, Wang, et al. studied the influence of soil lateral dilation behavior on embankment settlement by FEM[4, 5]. Loganathan, et al. analyzed the influence of soil lateral displacement on embankment settlement, and pointed out that it was a most effective measure to reduce embankment settlement by controlling lateral displacement of embankment slope feet[3].

To limit the lateral and compression deformation of soft soil within the scope of embankment loading, and to reduce embankment settlement, a ground improvement technology was proposed: a row of long piles with denser spacing were set out of the scope of embankment loading to limit lateral deformation of soft soil, short piles were set among the scope of embankment loading to reduce compression deformation of soft soil(shown in Fig. 1). Based on the ground improvement technology proposed in this paper, an theoretical analytical method for deformation of the composite foundation with lateral restriction under embankment load was established, and the calculation results were verified by the model test.

2. Calculation model and displacement variational method

2.1 Basic assumptions and calculation model

1) Highway is the line structure. Thus, the long direction can be regarded as infinite length. An arbitrary cross-section is defined as xy plane, and arbitrary ordinate is defined as z axes. Under embankment load, every

point in ground could merely move to x-direction and y-direction, could not move to z-direction. Therefore, this problem is a problem of plane strain.

2) It is assumed that all of the materials are homogeneous, isotropic and ideal elastic body(LU, et al 2010), Influence of the material deadweight is ignored.

3) The embankment load is defined as trapezia load, and is loaded upon the surface of reinforced area directly (as shown in Fig. 1). The load on the reinforced area is:

$$Q=\begin{cases}-q & (-L_1 \le x \le L_1)\\ -q(L_2+L_1-x)/L_2 & (L_1 \le x \le L_1+L_2)\end{cases} \tag{1}$$

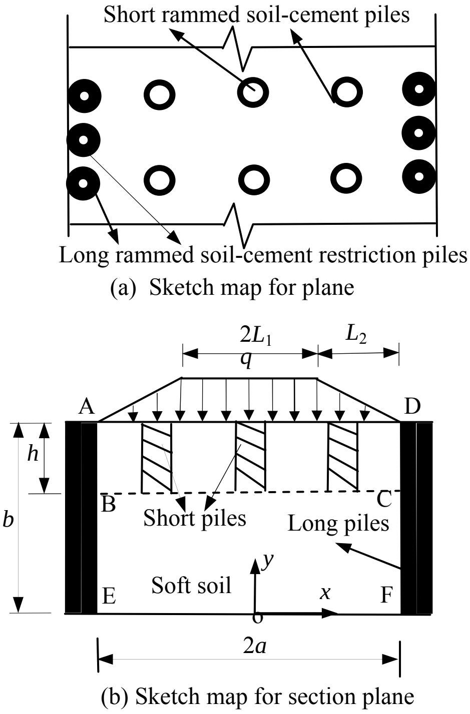


Fig.1 Analysis model on composite foundation with lateral restriction piles

4) Due to the restriction of lone piles, the level and vertical displacements of pile-soil interface AE and DF are assumed as zero, the deformation influence scope of the composite foundation with lateral restriction piles is AEFD area.

5) For simplifying the analysis, the piles and surrounding soils in the reinforced area of the composite foundation is transformed into isotropic elastic foundation, equivalent modulus E_1 is confirmed by area weighted method(Specifications for Design of Highway Subgrades (JTGD30-2004)), Ministry of Transport of the People's Republic of China) as following:

$$E_1 = mE_p + (1-m)E_s \tag{2}$$

where, E_p and E_s are the compression modulus of pile and surrounding soil, respectively. m is pile area replacement ratio.

2.2 Displacement variational method

1) Boundary condition of the displacement

Based on the aforementioned assumptions, the boundary condition of the displacement is:

$$\left.\begin{aligned} u(x,y)\big|_{x=\pm a}=0, v(x,y)\big|_{x=\pm a}=0\\ u(x,y)\big|_{y=0}=0, v(x,y)\big|_{y=0}=0\end{aligned}\right\} \tag{3}$$

where, $u(x,y)$ is x-direction displacement, $v(x,y)$ is y-direction displacement.

Based on this problem symmetry, $u(x,y)$ is odd function about x, and $v(x,y)$ was even function about x.

2) Displacement components and deformation energy

Functional expressions for displacement components are suggested as follows:

$$
\left.\begin{aligned}
u(x,y) &= A_1\left(\frac{x}{a}-\frac{x^3}{a^3}\right)\frac{y}{b}+A_2\left(\frac{x}{a}-\frac{x^3}{a^3}\right)\frac{y^2}{b^2}\\
v(x,y) &= B_1\left(1-\frac{x^2}{a^2}\right)\frac{y}{b}+B_2\left(1-\frac{x^2}{a^2}\right)\frac{y^2}{b^2}
\end{aligned}\right\} \tag{4}
$$

Contrast Eq. (3) and (4), the displacement components are satisfied with all of the displacement boundary conditions, symmetric and antisymmetric conditions.

Based on the elastic theory(XU 2001), the deformation energy of the reinforced area and the deformation influence area are obtained, respectively:

$$
U_1=\alpha_1\iint_{ABCD}\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\beta_1\frac{\partial u}{\partial x}\frac{\partial v}{\partial y}+\gamma_1\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2\right]dxdy \tag{5}
$$

$$
U_2=\alpha_2\iint_{BEFC}\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\beta_2\frac{\partial u}{\partial x}\frac{\partial v}{\partial y}+\gamma_2\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2\right]dxdy \tag{6}
$$

where, U_1 and U_2 are the deformation energy of the reinforced area ABCD and the deformation influence area BEFC, respectively. E_1 and E_2 are the compression modulus of the reinforced area ABCD and the deformation influence area BEFC, respectively. μ_1 and μ_2 are the Poisson's ratio of material in the reinforced area ABCD and the deformation influence area BEFC, respectively. $\alpha_i=E_i(1-\mu_i)/[(1+\mu_i)(1-2\mu_i)]$, $\beta_i=2\mu_i/(1-\mu_i)$, $\gamma_i=(1-2\mu_i)/[2(1-\mu_i)]$, $(i=1,2)$.

According to Fig. 1, the total deformation energies of the reinforced area ABCD and the deformation influence area BEFC are obtained by superposition method,

$$
U=U_1+U_2 \tag{7}
$$

3) Displacement variational equations and its solution

According to the distributing load shown in Figs. 1 and displacement component expressions Eq. (4), displacement variational equations of this question are obtained by the elastic theory as follows,

$$
\sum_m\left(\frac{\partial U}{\partial A_m}\right)\delta A_m+\sum_m\left[\frac{\partial U}{\partial B_m}-\int_{AD}Qv_m\big|_{y=b}\,dx\right]\delta B_m=0 \tag{8}
$$

The variable δA_m and δB_m are arbitrary absolutely, and did not rely each other, thereby, their coefficients in Eq. (8) must be zero, it may obtain,

$$
\left.\begin{aligned}
&\frac{\partial U}{\partial A_m}=0\\
&\frac{\partial U}{\partial B_m}=2\int_0^{L_1+L_2}Qv_m\big|_{y=b}\,dx
\end{aligned}\right\}(m=1,2) \tag{9}
$$

where, $v_1=(1-x^2/a^2)\,y/b$, $v_2=(1-x^2/a^2)\,y^2/b^2$.

Substituting Eqs. (1) and (7) into Eq. (9), and using Eqs. (4)-(6), the linear algebraic equations on coefficient A_m and $B_m(m=1,2)$ can be obtained, solving this linear algebraic equations, the undetermined coefficient A_m, $B_m(m=1,2)$ may be determined, respectively.

Using Eq. (4), the average settlement of ground can be obtained as follow:

$$
v_{ave}=\frac{2(B_1+B_2)}{3} \tag{10}
$$

where, B_1 and B_2 are function of the load, respectively.

3 .Contrast analysis of model test and calculating results

The model tests were performed in a indoor foundation pit with a size of 6.0×6.0×3.0m(length × width × depth).

The soil used in the model tests is non-saturate soft clay.

The diameter of the long restriction piles is the same with that of the short piles in the reinforced area, i.e. the diameter is 75mm. The pile material of all test piles were the mixtures, which consist cement, dry clay and water. In the mixtures, the cement grade is 325, the weight ratio of cement and dry clay is 1:9.

The soft clay was layered buried into the pit. After that, it had been lied statically a week. Then, wooden pile was pressed into the soft clay to form hole, respectively. After the wooden pile was pull out, the mixture was layered filled into the hole and rammed to form short soil-cement piles, the degree of compaction of pile body is 90%. Long rammed soil-cement restriction piles had been made since the short soil-cement piles in the reinforced area were completed, and the construction technics of long piles was the same as that of short piles. The length of long restriction pile was 2.8m, and the pile spacing and distribution is shown in Fig. 2(a).

After the test model had been completed one month, the physical-mechanical parameters of surrounding soil were obtained by soil tests(shown in Table. 1). The testing methods were respectively as following: water content was mensurated by drying method, unit weight was mensurated by cutting ring method, the other calculation parameters of soils were respectively mensurated by triaxial compression test, and compression modulus was mensurated by confined compression test, its value was ratio of 100kPa stress increment and corresponding strain increment. At the same, the physical-mechanical parameters of short soil-cement piles were obtained by conventional experiment (shown in Table. 2). The compression modulus was mensurated by unconfined compression test.

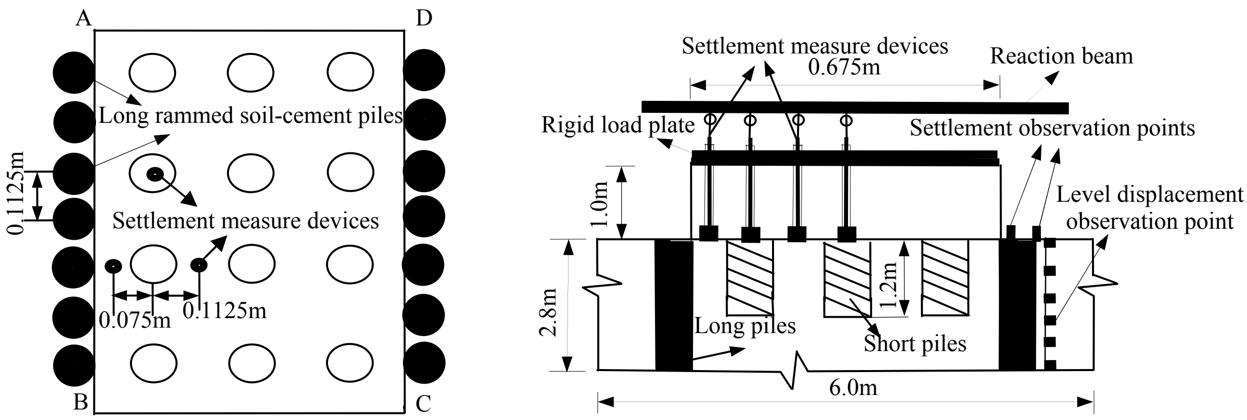
Table 1 Physical-mechanical index of the soil

Water content /%	Plasticity index	Liquidity index	Cohesion /kPa	Internal friction angle /^{o}	Characteristic value of bearing capacity /kPa	Compression modulus /MPa
30.8	21.7	0.42	9.4	8.2	56	3.4

Table 2 Physical-mechanical index of short soil-cement piles

Diameter /mm	Length /m	Pile amount	Pile spacing /mm	Compression modulus / MPa	Area replacement ratio /%
75	1.2	12	225	35.7	8.7

The static load test was performed after model test's manufacture finished 40 days. The distance from surface applied uniform load to the bottom of the foundation pit is h=2.8m, and the load was applied in the scope with 0.675×0.90 m(as shown in Fig.2 (a) ABCD area). In order to simulate the uniform load, the first grade load was offered by standard sands with 1.0 m thickness filled into the load box made from bamboo board along four sides of uniform load scope, the standard sand's density is 14.5 kN/ m^3. Before the test, the lubricating oil was painted in medial wall of the load boxes to reduce interface friction effect, respectively. The rubber plate with 0.675×0.90 m was placed upon the surface of the standard sands after the first grade load, and the rigid load plate with 0.675×0.90 m was placed on the surface of the rubber plate, the next different grades load were applied by jacks(shown in Fig.2 (b)), respectively. The static load tests were performed according to the "Technical Code for ground treatment of buildings" (JGJ 79-2002) strictly.



(a) Sketch map for plane with lateral restriction piles (b) Sketch map for section

Fig.2 Sketch map of model test

Ground settlement in the uniform load scope was mensurated by settlement measure device, the value was read by dial indicator. Ground settlement outside the uniform load scope was mensurated by the total station. Level displacement observation points were set outside the uniform load scope along foundation depth direction, and their spacing was 0.5 m, the value was read by JMD50 displacement sensor. Observation points position were shown in Fig.2 b).

When using the proposed method in this paper to calculate the model test, the vertical calculation depth was selected as b=2.8m. During the model test, the settlement and level displacement values of long piles and its outside soil were almost zero by the total station and JMD50 displacement sensor, respectively. The feasibility of the aforementioned assumption, the level and vertical displacements of the interface between the long pile and surrounding soil were zero in the composite foundation with lateral restriction piles, was verified. So, the calculation parameter 2a was selected as 0.675m.

Fig. 3 shows the settlement distributing situation of the composite foundation with lateral restriction piles, when the uniform load upon the composite foundation was 116kPa. From the test curve, it can be seen that the settlement of pile-top is smaller than that of surrounding soil, and it indicates that a certain depth scope of short piles is bearing negative friction.

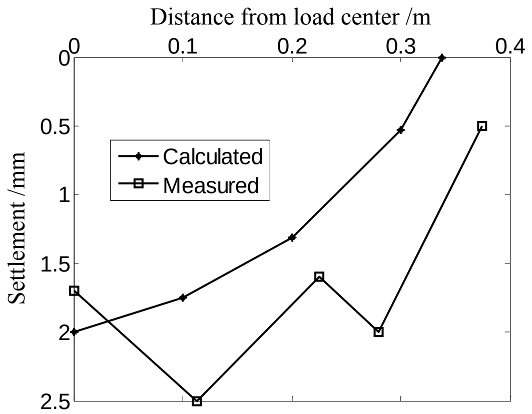


Fig.3 Settlement status of foundation

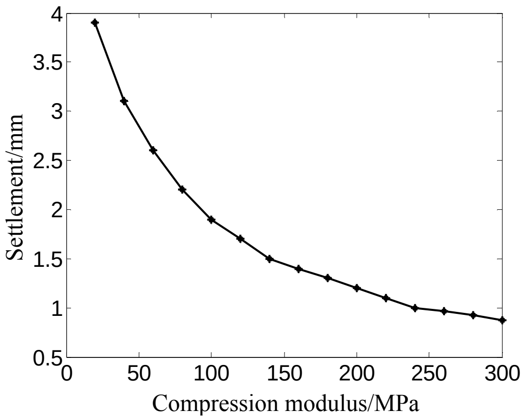


Fig.4 Influence of compression modulus on settlement

Fig. 4 shows the influence of the material compression modulus of the short piles on the average settlements of the composite foundation, when the uniform load upon the composite foundation was 116kPa. It can be seen that the average settlements reduce with the increase of the material compression modulus of the short piles. But the influence of the material compression modulus of the short piles on the average settlements is very small after the material compression modulus of the short piles is bigger than 150MPa. Therefore, for the composite foundation with rammed soil-cement piles, the material compression modulus of the rammed soil-cement piles is increased within a certain range, the settlement of the composite foundation may be reduced effectively.

Fig. 5 shows the relationship between load and average settlement of the composite foundation. It can be seen that the theoretical calculation results be close to the test results well. The feasibility of the proposed analyses methods and constructed displacement function are verified.

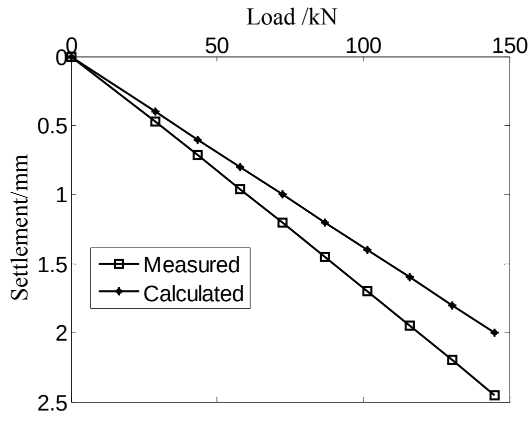


Fig.5 Realtion of load and average settlement

4. Conclusions

1) A new composite foundation technique for soft foundation improvement, setting lateral restriction piles at the composite foundation edges, has been proposed, and the larger proportion model test was performed. At the same time, expressions for displacement components satisfied with displacement boundary conditions were constructed, using displacement variational method, an approximate analytical algorithm for deformation of

Fig.5 Realtion of load and average settlement

composite foundation with lateral restriction under embankment load was established, and approximate analytical formula of the relationship between load and average settlement of composite foundation was deduced. It has some guidance meaning to engineering practice.

2) For the composite foundation with the rammed soil-cement piles, the material compression modulus of the rammed soil-cement piles is increased within a certain range, the settlement of the composite foundation may be reduced effectively.

Acknowledgements

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