# Comparison and analysis of pile-soil separate calculation and composite foundation calculation method for gravel pile reinforcement

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**Abstract:** This paper uses Indraratna seepage theory, Han pile-soil seepage theory and composite foundation theory to establish three plane strain models. Through finite element calculations, the changes in pore pressure and settlement are compared, and the following laws are found: (1) The model established by the composite foundation theory cannot reflect the objective laws of seepage and deformation; (2) In the case of multiple piles, there is no difference in settlement between Han pile-soil seepage theory considering the bearing characteristics of gravel piles and Indraratna seepage theory without considering the bearing characteristics of gravel piles. (3) The settlement value obtained by the principle of composite foundation is much smaller than the settlement value obtained by the separate calculation of pile and soil.

## 0. Preface

Nowadays, in engineering design, the foundation reinforced by gravel piles is generally analyzed based on the theory of composite foundation. In addition, some researchers have adopted the method of separate calculation of piles and soils, using the plane strain model of gravel piles to strengthen the foundation for calculation and analysis. Based on Indraratna [1] sand well seepage theory, Han [2] pile-soil seepage consolidation theory solution and gravel pile reinforced composite foundation principle, this paper establishes plane strain model under the condition of multiple piles, and compares the settlement and pore pressure changes of different models when they are consolidated.

## 1. Theory

Assuming that the gravel piles are distributed like plum blossoms, the spacing of gravel piles is 4m, and the effective pile diameter is 1m, the influence radius of a single gravel pile is 2.1m. The conversion formula given by Tan [3] is converted into an equivalent plane strain model, the 1/2 pile spacing B is 1.86m, the gravel pile radius $B_c$ is 0.10556m, and the soil thickness is 10m. Based on this, the establishment of its equivalent two-dimensional generalized model of gravel piles to strengthen the foundation is shown in Figure 1. Due to the axis symmetry, 2.5 piles are selected in the figure.

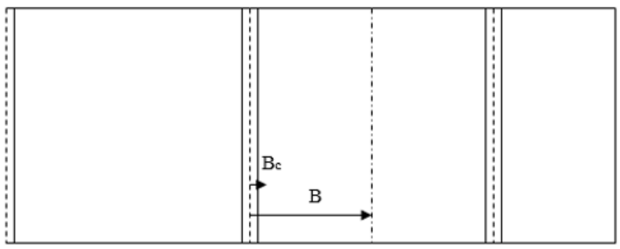


**Figure 1** Two-dimensional generalized model of the foundation reinforced by gravel piles

### 1.1 Indraratna equivalent plane strain model

Indraratna uses Hansbo's sand well seepage consolidation theoretical solution, only considering the drainage effect of gravel piles, and obtains the permeability coefficient under plane strain conditions.

$$k_{x,\,pl}=\frac{2\alpha}{\ln(n)-0.75}\frac{B^2}{R^2}k_{x,\,ax} \qquad (1)$$

In the formula: n is the aperture ratio, $\alpha=\frac{1}{3}+\frac{b_c}{2B}-\frac{b_c}{6B}-\frac{b_c^2}{6B^2}+\frac{b_c^2}{2B^2}-\frac{b_c}{B}$, $k_{x,\,pl}$ and $k_{x,\,ax}$ respectively represent the permeability coefficient under axisymmetric conditions.

### 1.2 Han pile-soil seepage consolidation theory solution

In Han's theoretical solution of pile-soil seepage consolidation, he considered the two roles of gravel piles to share additional load and drainage. In the conversion, the genetic algorithm is used to solve the equation (2), so

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that the average degree of consolidation under the plane strain condition matches the average degree of consolidation under Han's pile-soil axisymmetric condition.

$$\sum_{m=1}^{\infty}\frac{2}{M^2}\exp(-M^2T_v)=\exp(\frac{-8T_r}{f(n)}) \qquad (2)$$

Consolidation matching is shown in Figure 2

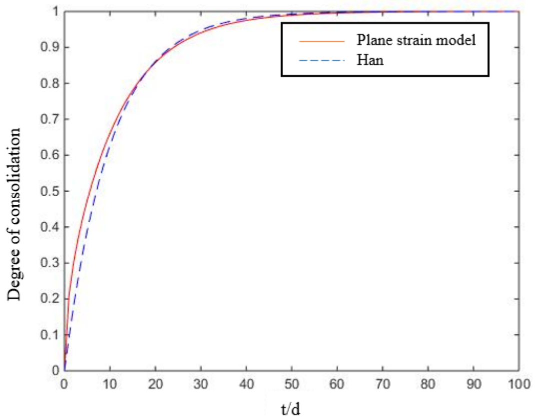



**Figure 2** Schematic diagram of consolidation degree matching

### 1.3 Composite foundation

In engineering, the elastic modulus and deformation modulus of composite foundation are generally calculated according to the weighted average method according to the area proposed by Schweiger and Pande [4], as shown in equation (3).

$$E_{cs}=(1-\alpha)E_s+\alpha E_c \qquad (3)$$

In the formula: $\alpha$ is the area replacement rate.

Regarding the permeability coefficient, the permeability coefficient of the composite foundation is generally adjusted so that the degree of consolidation obtained by the sand well consolidation theory matches the degree of consolidation obtained by the one-dimensional seepage consolidation theory of Terzaghi in the composite foundation.

Barron [5] obtained that the consolidation degree of seepage in sand wells at equal strain is

$$U_r=1-\exp[\frac{-8T_r}{f(n)}] \qquad (4)$$

## 2. Modeling

According to the above method, determine the corresponding model size and material parameters. The corresponding model size is shown in Figure 1, and the determined parameters are shown in Table 1. The first line in the table is the original parameter, and the second, third, and fourth lines are the calculated parameters converted according to the theory described above. Among them, the permeability coefficient of the composite foundation is adjusted to match the solution of the Terzaghi seepage and consolidation theory, as shown in Figure 3.

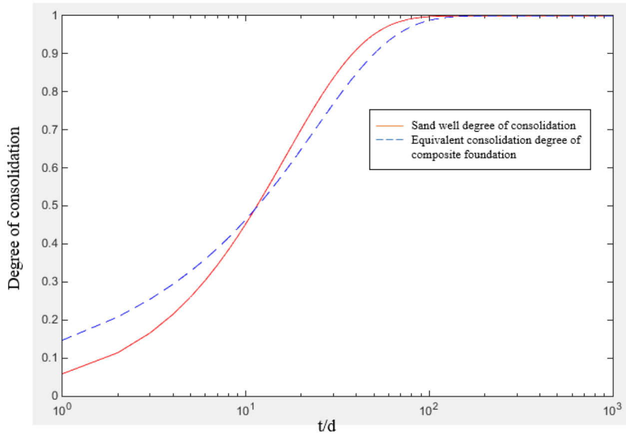
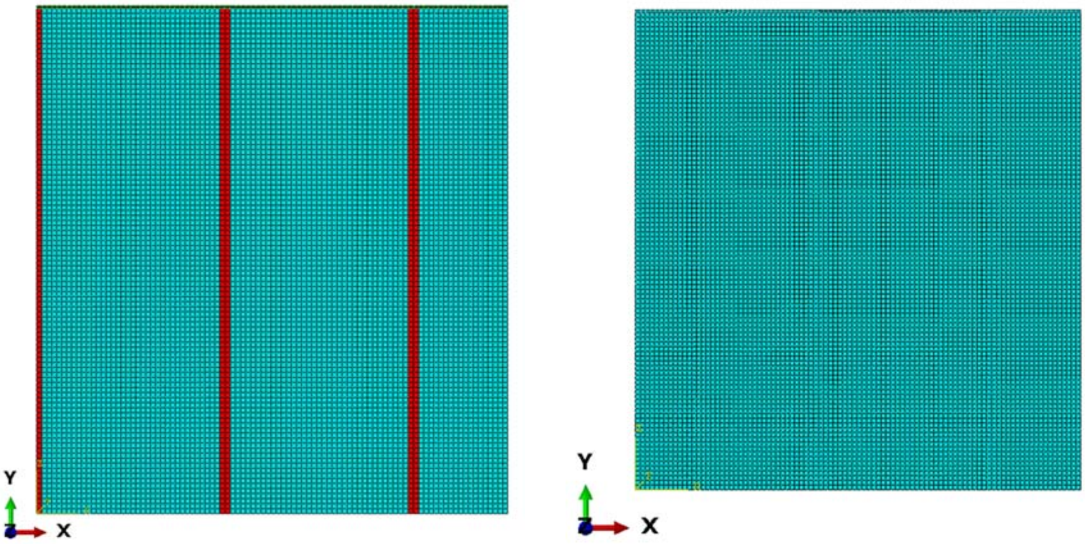



**Figure 3** Comparison between consolidation degree of sand well seepage and theoretical consolidation degree of composite foundation

**Table 1** Material parameter table

| Model | $\gamma_s=\gamma_c$ kN·m$^{-3}$ | $\nu'$ | $E_s$ MPa | $E_c$ MPa | $k_h$ m·s$^{-1}$ | $k_v$ m·s$^{-1}$ | $c_s'$ kPa | $\varphi_s'$ deg | $c_c'$ kPa | $\varphi_c'$ deg |
|---|---|---|---|---|---|---|---|---|---|---|
| Original parameter | 15 | 0.3 | 3 | 30 | $3.00\cdot10^{-9}$ | $3\cdot10^{-9}$ | 0.1 | 22 | 1 | 40 |
| Separate calculation of pile and soil 1 | 15 | 0.3 | 3 | 30 | $2.04\cdot10^{-9}$ | $3\cdot10^{-9}$ | 0.1 | 22 | 1 | 40 |
| Separate calculation of pile and soil 2 | 15 | 0.3 | 3 | 30 | $1.55\cdot10^{-9}$ | $3\cdot10^{-9}$ | 0.1 | 22 | 1 | 40 |
| composite foundation | 15 | 0.3 | 9.48 | / | $4.86\cdot10^{-8}$ | $4.86\cdot10^{-8}$ | 0.1 | 22 | 1 | 40 |

The finite element model is shown in Figure 4, with 100kPa load applied, and the consolidation changes of three different plane strain models are obtained.

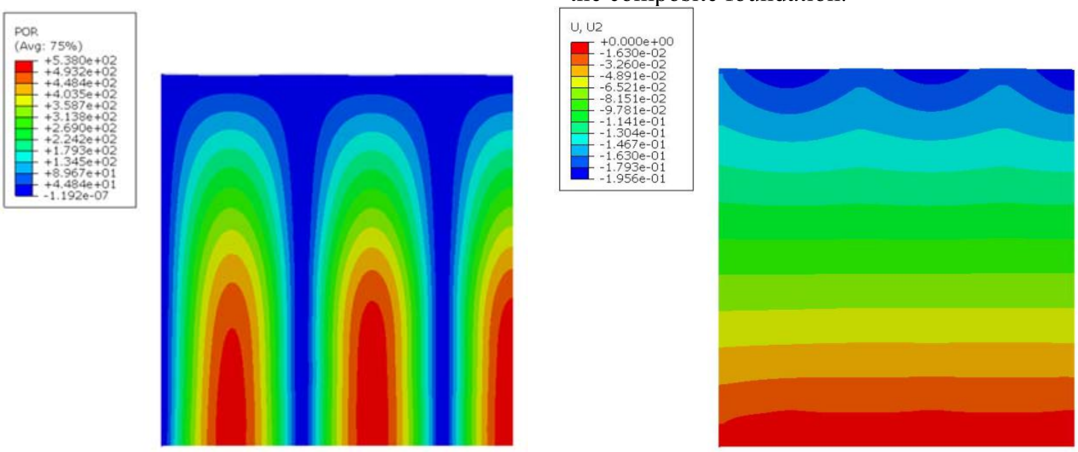



(a) Separate calculation of pile and soil (b) Composite foundation

**Figure 4** Finite element model

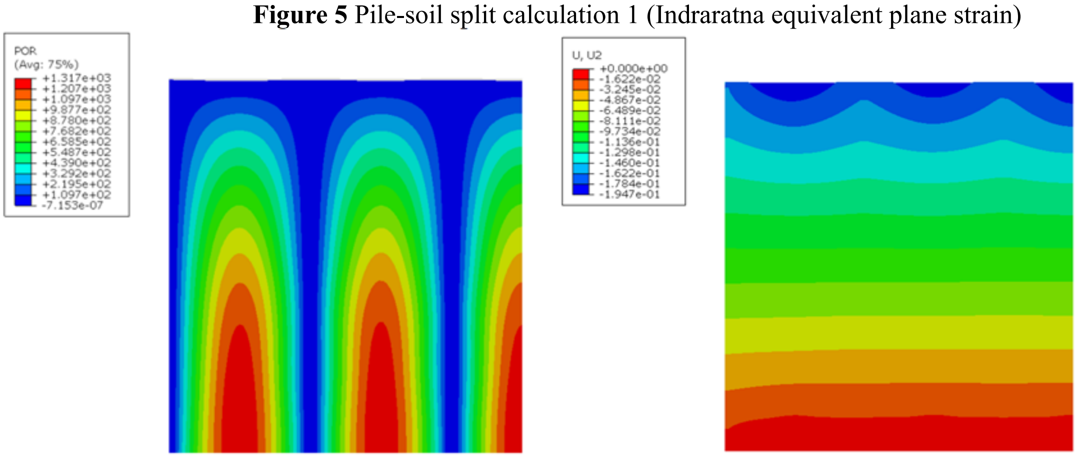
## 3. Analysis

The pore pressure and settlement conditions of the three plane models after 100 days of consolidation are shown in Figs. 4-6. It can be seen from the figure that under the condition of separate calculation of pile and soil, there is a clear gap between the pore pressure of gravel pile and the soil between piles. It shows that there is a tendency for water in the soil between the piles to seep into the gravel piles. Under the composite foundation, this tendency is obviously not reflected. It can be seen from the settlement diagram that near the surface of the soil layer, there is a significant gap between the settlement of the gravel pile and the soil between the piles, which is also unreactive in the composite foundation.




(a) Pore pressure /Pa (b) Settlement /m

**Figure 5** Pile-soil split calculation 1 (Indraratna equivalent plane strain)




(a) Pore pressure /Pa (b) Settlement /m

**Figure 6** Pile-soil separation 2 (Han pile-soil seepage consolidation)

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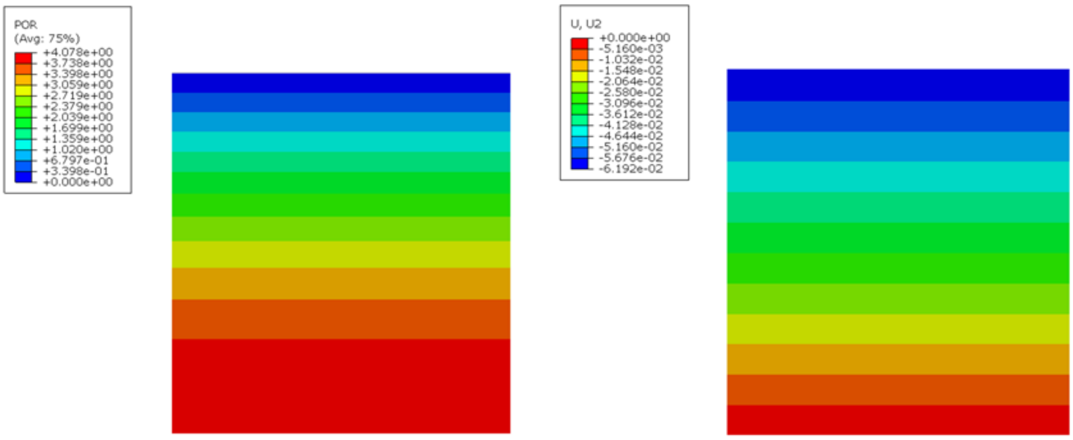
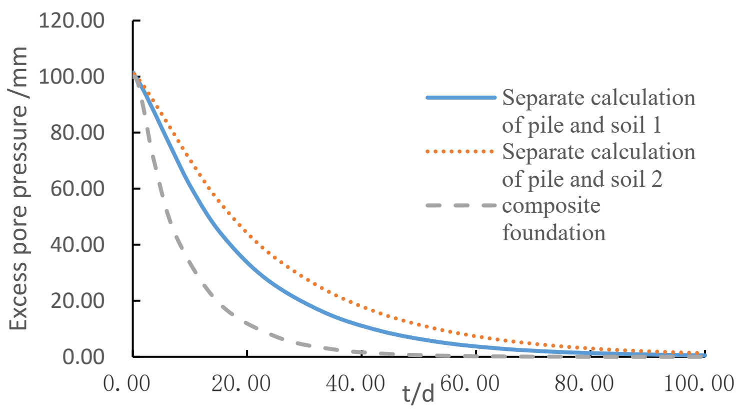


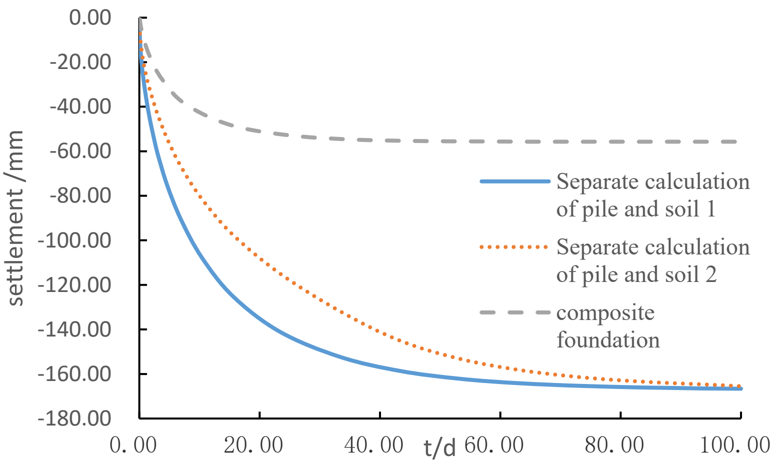

(a) Pore pressure /Pa (b) Settlement /m

**Figure 7** Composite foundation

According to the distribution law of displacement and pore pressure, choose a point near the surface of the soil layer as the settlement curve with time and a point near the bottom surface of the soil layer as the curve of pore pressure with time as shown in Figure 7 to further understand its changes. It can be seen from the figure that the changes of excess pore pressure and displacement of the two methods of pile-soil separate calculation are close. It can be analyzed that the Indraratna's pile-soil separation method, which does not consider the gravel piles to share the additional load, has a 31.6% larger permeability coefficient than Han's pile-soil separation method, which considers the gravel piles to share the additional load. But under the condition of multiple piles, it has little effect on the settlement result. In addition, considering that the theoretical settlement value of the composite foundation is much smaller than the settlement value calculated separately for the pile and soil, the settlement value of the composite foundation is about 56mm at the moment when the settlement of the consolidation 100d stabilizes. The settlement value of the two pile-soil separate calculation models is 166mm, and the settlement value of the pile-soil separate calculation is about 3 times the settlement value of the composite foundation. Analyze the specific reasons. First, it can be seen from the excess pore pressure curve that the composite foundation is consolidated faster and the excess pore pressure dissipates faster; second, it can be seen from the deformation modulus of the material parameters that the composite foundation theory greatly increases the deformation modulus of the soil.




（a）Excess pore pressure /kPa




（b） settlement /m

**Figure 8** Changes in excess pore pressure and settlement with time

## 4. Conclusion

In this paper, three plane strain models are established through Indraratna seepage theory, Han pile-soil seepage theory and composite foundation theory. By comparing the changes in pore pressure and settlement, the following conclusions are made:

(1) The model established by the composite foundation theory cannot reflect the objective law of seepage, and cannot reflect the seepage of soil between piles into gravel piles. In addition, the settlement diagram cannot reflect the settlement difference between the gravel pile and the soil between the piles.

(2) Under multiple pile conditions, the Han pile-soil seepage theory considering the pressure-bearing properties of gravel piles and the Indraratna seepage theory without considering the pressure-bearing properties of gravel piles have basically no difference in settlement analysis.

(3) The settlement value obtained by the principle of composite foundation is much smaller than the settlement value obtained by the separate calculation of pile and soil. There are two reasons for this. First, the equivalent permeability coefficient is large and the excess pore pressure dissipates faster; second, the composite foundation theory greatly increases the deformation modulus of the soil.

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