Study on the role of cushion of composite ground and the choice of its depth

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Abstract. Cushion design on CFG pile composite foundation is an important part of CFG pile. Through theoretical analysis, the mechanism of cushion improving composite foundation is obtained, and the relationship curve of cushion thickness, modulus, pile-soil stress ratio, length of negative friction zone and settlement is analyzed, so as to provide basis for cushion thickness design of CFG pile composite foundation.

1. Introduction
Cement fly ash gravel pile, referred to as CFG pile, is made of gravel, gravel, sand and fly ash mixed with an appropriate amount of cement and water mixing. CFG pile is loaded by pile body and soil between piles. The results show that the essence of pile-soil joint work is to adjust the relative deformation between piles and soils. Because the strength and modulus of pile is much higher than that of inter-pile soil, the deformation of pile is much smaller than that of inter-pile soil under the action of applied load, so it is difficult for inter-pile soil to function. In order to give full play to the bearing characteristics of composite foundation, a cushion layer is arranged under the foundation cap to improve the pile and soil load distribution in composite foundation.

Cushion is the core technology of composite foundation. Many characteristics of composite foundation are related to cushion. In the composite foundation, the cushion plays the role of ensuring the Shared load of pile and soil. The proper thickness of cushion can make the load sharing ratio between piles reasonable, reduce the stress concentration of foundation bottom surface, and improve the bearing capacity of foundation.

2. The role of the mattress
CFG pile composite foundation is composed of pile body, soil between piles and cushion. The thickness and material of cushion will directly affect the scientific, rationality and economy of composite foundation. Its functions are as follows:

2.1. Ensure that the pile and soil share the external load
For CFG pile composite foundation, the foundation is connected with the pile and the soil between piles through the cushion of thickness H.
When cushion thickness, pile and soil between piles work like pile foundation. Under a given load, the pile bears more load. With the increase of time, the pile will have a certain settlement and the load will gradually transfer to the soil.

When $H=0$, when the pile ends fall on the hard and dense soil or rock, the settlement of the pile is small, and the amount of load transferred from the pile to the soil between the piles is small, so the bearing capacity of the soil between the piles is difficult to play.

When $H=0$, when the pile ends fall on the general soil layer, the foundation under the external load, with the extension of time, the settlement deformation of the foundation and the pile continues to increase, the soil load between the piles continues to increase, and the load borne by the pile correspondingly decreases.

When $H>0$, that is, when a certain thickness of cushion is set between the foundation and the pile, after the foundation bears the external load, no matter what soil layer the pile ends fall on, the pile and the soil between the piles will have settlement deformation. As the deformation modulus of the pile body is much larger than that of the soil around the pile, the deformation of the pile is much smaller than that of the soil. At this time, the pile can Pierce into the cushion layer upward. With this process, the cushion material is constantly adjusted and added to the soil between piles to ensure that the foundation always transmits part of the load to the soil between piles, so as to ensure that the pile and the soil between piles always participate in the work under any load. According to a large number of test results, the pile top stress $\sigma_0$ and inter-pile soil surface stress $\sigma_s$ remain constant, that is, the pile-soil stress ratio $n = \sigma_p / \sigma_s$ is constant, although the deformation of the pile top and the soil surface around the pile continues to increase.

2.2. Adjust the vertical load sharing ratio between pile and soil

The vertical load sharing ratio of pile and soil in composite foundation is usually expressed by the pile and soil load sharing ratio $\delta_p$, $\delta_s$:

$$\delta_p = \frac{P_p}{P}, \quad \delta_s = \frac{P_s}{P}$$

$A$ is the base area, $A_p$ is the total cross-sectional area of pile, $A_s$ is the total cross-sectional area of soil between piles under the basement. When the area displacement rate $m = A_p / A_s$ is determined, the load sharing ratio of pile and soil and the stress ratio of pile and soil can be converted to each other. When the load sharing ratio $\delta_p$ and $\delta_s$ of pile and soil are known, the pile top stress and soil stress between piles can be obtained:

$$\sigma_p = \frac{\delta_p P}{A_p}$$

The soil stress ratio between piles is:

$$\rho_s = \frac{\delta_p P}{A(1 - m)}$$

Then the pile-soil stress ratio $n$:

$$n = \frac{\sigma_p}{\sigma_s} = \frac{(1 - m)\delta_p}{m\delta_s}$$

When the pile-soil stress ratio $n$ is known, the force balance equation for any load expressed by pile-soil stress ratio is:
Then, the vertical load sharing ratio of pile and soil can be obtained:

\[ \delta_p = \frac{nm}{A[1 + m(n - 1)]} \]

\[ \delta_s = \frac{(1 - m)}{1 + m(n - 1)} \]

Most of the pile-soil stress ratio \( n \) in CFG pile composite foundation varies between 10~40, and can reach about 100 in soft soil. The percentage of load borne by pile in the total load is generally between 40% and 75%.

2.3. Adjust the horizontal load sharing between pile and soil

CFG pile is mainly used to transfer the vertical load. Since the pile body of CFG pile is not reinforced, how to overcome the horizontal load of CFG pile composite foundation? The analysis is as follows:

When the thickness of cushion \( H = 0 \), the foundation is subjected to the vertical load \( P \) and the horizontal load \( Q \). According to the previous description, under the vertical load, the pile load sharing ratio is small, while the soil load sharing ratio \( \delta_s \) is small (FIG. 2a).

Assuming that the horizontal load transferred to the pile is \( Q_p \) and the horizontal load transferred to the soil between the piles is \( Q_s \) under the condition of no burial depth, the following equation holds:

\[ Q = Q_p + Q_s \]

And there was a: \( Q_s = \mu P_s \)

\( \mu \)—friction coefficient between foundation and soil varies from 0.25 to 0.45.

Because \( H = 0 \), \( P_s \) is small, the \( Q_s \) are also small, at this time to bear horizontal load \( Q \) is mainly composed of piles, \( Q_p \) is large, as shown in figure 2, figure of \( \tau_p \) for cap shear stress, \( \tau_s \) for soil shear stress between piles.

\( H \) indicates when the mattress thickness 0 and increases to a certain value, the effect on the shear stress on the pile top and soil between piles \( \tau_p \) and \( \tau_s \) differ not quite, on the top of the pile shear \( Q_p = mA\tau_p \) (\( m \) is replacement rate, \( A \) is a floor area). It can be seen that the ratio of shear stress \( Q_p \) to the total horizontal load of pile is roughly the same as the displacement rate \( m \). As shown in FIG. 2, and at this time, the horizontal load borne by the pile is very small, and the horizontal load is mainly borne by the soil between the piles.

Figure 2. The shear stress of pile and soil
2.4. Reduce the stress concentration of pile top on foundation bottom

When the cushion thickness $H=0$, the stress concentration of CFG pile on the underside of the foundation is similar to that of the reinforced concrete pile on the cap or the foundation on the pile, so the impact failure of the pile on the foundation should be considered.

When $H\neq 0$ and increases to a certain value, the distribution of base pressure is similar to that of natural foundation. In general, when the thickness of the cushion is $H>10\text{cm}$, the stress concentration of the pile on the underside of the foundation has weakened significantly. When $H=30\text{cm}$, the stress concentration basically disappear.

3. Influence of cushion on settlement of CFG pile composite foundation

3.1. Influence of cushion modulus on settlement of CFG pile composite foundation

According to the curve in FIG. 3, as the modulus of cushion decreases, the pile-soil stress ratio decreases correspondingly, that is, the load borne by pile decreases and the load borne by soil between piles increases. Therefore, the soil between piles is further compressed and settled, and the soil has a large downward displacement relative to the pile. The length of the resulting negative friction zone also decreases with the increase of cushion modulus. As shown in FIG. 4, the increase of the length of the negative friction zone further increases the settlement of the foundation. This is because the longer the negative friction area, the greater the downward side friction resistance on the pile, and the greater the dead weight of the soil itself. However, the negative friction zone is not too long, generally within 2cm from the pile top. FIG. 5 shows that the settlement increases with the decrease of cushion modulus. Therefore, in the design of composite foundation, we should choose the appropriate cushion modulus to adjust and control the settlement of the foundation.

![Figure 3. The relationship curve of pile-soil stress ratio and cushion modulus](image)

![Figure 4. The relationship curve of minus friction zone length and cushion modulus](image)

![Figure 5. The relationship curve of foundation settlement and cushion modulus](image)
3.2. The influence of cushion thickness on CFG pile

The thickness of cushion is also reflected by the influence of degree on CFG pile through the distribution of soil load between pile and pile. When the upper load is constant and the cushion material is constant, the relationship between cushion thickness and the pile-soil stress ratio and the length of negative friction zone of composite foundation is shown in FIG. 6 and 7.

![Figure 6. The relationship curve of pile-soil stress ratio and cushion thickness](image)

![Figure 7. The relationship curve of minus friction zone length and cushion thickness](image)

![Figure 8. The relationship curve of total settlement and cushion thickness](image)

FIG. 6 shows that the thickness of cushion between 10 and 45cm has a great regulating effect on the stress ratio of pile and soil. When the cushion layer increases, its ability to adjust the load sharing of pile and soil is obviously weakened. FIG. 7 shows that with the increase of cushion thickness (within the range of 10 – 45cm), the length of the negative friction zone of pile increases relatively large, but the increase slows down after 45cm and basically remains at about 1.7m. At the same time, it can be seen from FIG. 8 that the total settlement increases with the increase of cushion thickness within the interval of 10-45cm. The reason is that during the period of the thickness, thickness of cushion the more load sharing between pile soil, the greater the resulting in the increase of soil between piles settlement, pile of reverse Pierce also increased at the same time, combined with compression deformation of cushion itself, caused the whole settlement of composite foundation has increased, and the plastic deformation part held a larger proportion in the total settlement. However, when the cushion thickness is greater than 45 cm, the total settlement decreases significantly with the increase of the cushion thickness. This is because when the cushion reaches a certain thickness, the load is constant, and has been fully adjusted, the pile-soil stress ratio is basically unchanged or changes little, and the settlement basically does not increase. After the cushion thickness exceeds a certain value, the composite foundation effect will not be obviously, will gradually transition to the cushion and the reinforcement area of the double layer foundation. The total settlement is composed of the deformation of the cushion, the deformation of the reinforcement area and the deformation of the underlying layer.
4. Conclusion
By comparing the references with other measured data, this paper analyzes the role of cushion in CFG composite foundation and the influence of cushion thickness on the load of CFG pile composite foundation, and draws the following conclusions.

Under the foundation, a cushion of a certain thickness is set. Under the action of external load, the pile body penetrates upward, and the cushion material is constantly adjusted and added to the soil between the piles, which ensures that the foundation always transmits part of the load to the soil between the piles, so that the pile body and the soil between the piles share the external load, and reduces the stress concentration of the pile top on the bottom surface of the foundation. At the same time, the cushion can reduce the horizontal shear stress borne by the pile, which is the horizontal load as long as the soil between the piles bears, to prevent the pile from horizontal fracture.

The stress ratio of CFG pile soil decreases with the increase of cushion thickness, but when the thickness increases to a certain degree (>45cm), the stress ratio of CFG pile soil becomes slower and slower, and the length of negative friction zone does not change significantly. The settlement increases with the thickness of the mattress when the mattress thickness is between 10 and 45cm. However, as the thickness increases, the settlement change is no longer significant. According to various factors, the thickness of mattress is recommended to be 10~45cm.

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