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Application Research of CFG Piles in the Treatment of Soft Soil Foundations for High-Speed Railways

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Abstract: In the construction of high-speed railways in our country, various complex terrains and geologies are often encountered. Therefore, the treatment of special subgrades, especially the reinforcement of soft soil subgrades, becomes extremely important. Currently, there are many methods for reinforcing weak and soft soil foundations, and during construction, appropriate and economical treatment methods should be selected based on the actual site conditions. This article intends to use the reinforcement treatment of the subgrade in the section from DK30+000 to +347.62 of the Ningbo-Hangzhou Passenger Dedicated Line as a basis to discuss the reinforcement of soft soil foundations and the application of CFG piles in soft soil foundations.

Keywords: Soft soil foundation, CFG pile, Foundation treatment.

1. Introduction

High-speed railways are a significant achievement in railway construction worldwide, providing a safe and reliable means of transportation for the majority of people. Notably, significant progress has been made in the treatment of railway composite foundations both domestically and internationally. This paper aims to develop a rational and cost-effective solution based on the existing route of the Ninghang Passenger Dedicated Line, meeting the requirements for soft soil foundation to the maximum extent.

According to the "Classification Standard for Railway Engineering Geotechnical Conditions," soft soil generally refers to fine-grained, cohesive soils deposited in static or slow-flowing water environments. These soils typically have a natural moisture content greater than the liquid limit, high organic matter content, large natural void ratio, high compressibility, low strength, poor permeability, and low bearing capacity. They can exist as soft plastic or slightly dense saturated silts. Geologically speaking, soft soil is considered a special type of soil, while loose soft soil does not fall under the category of special soils. The identification of loose soft soil is an important factor in the preliminary estimation of railway construction budgets. However, there is no precise definition or criteria for loose soft soil. The concept of loose soft soil is introduced in the design and construction process to meet the requirements of settlement calculation for the foundation.

2. Comparison of Treatment Methods for Loose Soft Soil Foundations

2.1. The difference between loose soil and soft soil

Loose soft soil shares similar characteristics with soft soil, such as high natural moisture content, low strength, good compressibility, and poor permeability. Due to the low bearing capacity of loose soft soil foundations, engineering safety issues such as collapse and settlement deformation often occur, which can significantly impact project safety and timeline. When constructing roads in areas with soft soil, various issues can arise, including severe subsidence during the construction process or several years after the operation begins. When encountering soft soil foundations that do not meet stability conditions, soil foundation treatment becomes necessary. The primary concerns for loose soft soil foundations are the stability of embankments and settlement deformation of the foundation. However, the calculation of embankment deformation can only be done when the embankment meets stability conditions. Construction in loose soft soil areas has always been a challenging aspect of railway construction due to the unfavorable engineering properties of loose soft soil. Destruction of loose soft soil embankments is mainly caused by the instability and sliding of embankment slopes. Factors such as excessive construction speed, steep embankment slopes, or insufficient foundation bearing capacity to withstand the load from the superstructure can contribute to this issue. Special reinforcement measures are required when dealing with soft soil foundations that do not meet stability conditions. Currently, there is rich experience both domestically and internationally regarding reinforcement techniques for loose soft soil foundations.

2.2. Treatment Methods for Loose Soft Soil Foundations

The table below presents several basic methods of ground treatment.

Each of these treatment methods has its own characteristics, applicability, and existing issues. When using them, appropriate treatment methods should be selected based on their advantages and disadvantages.

The table below introduces the advantages and disadvantages of several common foundation treatment methods for comparison and selection during design:

Table 1. Ground improvement methods

classification	the dynamic compaction method.	substitution method	drainage consolidation method	composite ground improvement method	Other method
treatment method	dynamic compaction method	excavation and backfilling method	preloading method	sand pile	reversed pressure method
	impact compaction method	stone dumping and consolidation method	sand cushion preloading method	crushed stone pile	geosynthetic reinforcement method
	the blasting method.	lightweight material replacement method	the sand compaction pile method.	Steel slag pile	freezing method
		tire soil	preloading method using geotextile drainage bags	deep soil mixing pile	sintering method
			preloading method using plastic drainage boards	high-pressure rotary jet grouting pile	
			vacuum preloading method	root pile	
			electro-osmotic preloading method	CFG pile	
			water-induced preloading method	concrete thin-walled pipe pile	
				prestressed concrete pipe pile	

Table 2. Advantages and disadvantage of common foundation treatment methods

methods	advantage	disadvantage
Dynamic compaction	can be translated into English as follows: "The construction process and equipment are relatively simple, saving materials, and can be used for various types of foundations	can be translated into English as: "During construction, there is significant noise which may have a significant impact on the surrounding residents. The long construction period may also affect nearby buildings
Replacement method	can be translated into English as: "The construction process is simple and can effectively mitigate the adverse effects of weak and soft soil foundations.	can be translated into English as: "It causes significant environmental pollution, has high costs, and is only suitable for treating shallow soil within 3 meters
Dewatering and consolidation method	can be translated into English as "Low cost, simple process	can be translated into English as: "It has a long construction period and limited treatment depth. It is generally used for treating soft soil at depths ranging from 4 to 12 meters
Composite ground improvement method	can be translated into English as: "The construction period is short, the installation depth is deep, and the reinforcement effect is good	can be translated into English as: "The construction process is complex, and the project cost is relatively high compared to other methods. It is generally suitable for construction and building on bridge heads and deep soft soil (10 to 20 meters). For soft soil foundations exceeding 20 meters, the best treatment method is to construct an elevated bridge, but it comes with high costs

CFG piles are abbreviated as Cement Fly-ash Gravel piles. Cement Fly-ash Gravel piles are composed of gravel, stone chips, sand, fly ash, and cement mixed with water. They are made using various pile driving machines to form piles with variable strength. CFG piles are a type of low-strength concrete piles that can effectively utilize the bearing capacity of the soil between the piles. They transfer loads to the deep foundation and offer excellent technical performance and economic benefits.

3. Engineering Examples

The Ning-Hang Intercity Railway line starts from Nanjing South Station in the north and ends at Hangzhou East Station in the south, with a total length of 256 km. There are a total of 11 stations along the line. This project is a double-track high-speed railway, designed for a speed of 350 km/h. The construction is jointly organized by the Ministry of Railways, Jiangsu Province, and Zhejiang Province. With a designed speed of 350 km/h, the single-direction transportation capacity can reach 80 million passengers per year.

The surface layer consists of topsoil and fill soil (Q4ml), mainly composed of fine-grained clay with a grayish-yellow color. It is soft and easily moldable, with an approximate thickness of 0.5m. Below the surface layer is an alluvial deposit (Q4al+pl) composed of fine-grained clay. This layer is plastic in nature and has a grayish-yellow color, with a thickness ranging from approximately 2.3 to 4.9m. Beneath the alluvial deposit, there is a layer of hard, compacted clay with a grayish-yellow to reddish-brown color. This layer has a harder consistency compared to the previous layer and has a thickness ranging from approximately 4 to 7.6m.

The underlying bedrock consists of the Middle Jurassic Tongsan Formation (J2t) sandstone. The sandstone exhibits varying degrees of weathering, ranging from fully weathered to weakly weathered. The fully weathered sandstone appears grayish-yellow or purplish-red and has a sand-like texture. It has a thickness ranging from 1.4 to 8.5m. The strongly weathered sandstone is predominantly grayish-yellow and appears more fragmented, with well-developed joints and fissures. It has a thickness range of 2 to 7.2m. The weakly weathered sandstone retains a relatively intact rock structure and is relatively hard.

(4) Q3al+Pl fine-grained clay, plastic, grade II; W=26.27%, γ=19.4 kN/m3, e=0.79, Cu=31.67 kPa, Φu=14.6°, average SPT N-value=14.95 blows, Es=6 MPa, σ0=150 kPa.

(4) Q3al+Pl silty clay, stiff-plastic, Class III; W=24.18%, γ=19.6 kN/m3, e=0.74, Cu=43.67 kPa, Φu=12.23°, average SPT N-value=13.9 blows, Es=8 MPa, σ0=180 kPa.

(8) 2-1 Sandstone, fully weathered, grade III; Cu=45 kPa, Φu=20°, average Standard Penetration Test (SPT) N-value=13.37 blows, Es=10 MPa, σ0=200 kPa.

The entire section consists of loose and soft soil as the subsoil. The peak ground acceleration during earthquakes is less than 0.05g. The upper part of the groundwater is from the Quaternary aquifers, with a burial depth of 1 to 3 meters and well-developed. The lower part does not have developed groundwater in the fissures of the bedrock within the sandstone. The primary source of groundwater recharge comes from atmospheric precipitation, which drains into the low-lying areas through runoff. The stable water level of the groundwater ranges from 0.2 to 1.8 meters. Both surface water and groundwater are non-erosive, and the carbonation environment conditions are classified as T2.

4. Case Study

4.1. Case Calculation

4.1.1. Load Composition

After the completion of the entire project and the commencement of normal train operations, the loads borne by the foundation can be classified into dynamic loads and static loads. Static loads mainly include the weight of embankment fill, the upper structure of the track, and the weight of the trains. Dynamic loads primarily refer to the loads generated by trains during high-speed operations.

4.1.2. Calculation of Self-weight Stress

the heaviness of natural water$\gamma_w = 9.8\mathrm{KN/m^3}$

Self-weight stress is calculated using effective unit weight

The self-weight stress at any point below the ground surface can be calculated using the following formula:

$$q_z = \sum \gamma_{ieffective} h_i$$

h_i — thickness of each layer

$\gamma_{ieffective}$ — effective unit weight of each layer

$$q_{\text{Silty clay，soft plastic}} = 15 \times 0.5 = 7.5$$

$$q_{\text{Silty clay，pliable}} = 19.4 \times 3.6 = 69.84$$

$$q_{\text{Silty clay，hard plastic}} = 19.6 \times 5.8 = 113.68$$

$$q_{\text{sandstone，complete weathering}} = 24 \times 4.9 = 117.6$$

$$q_{\text{sandstone，strong weathering}} = 22.5 \times 2.72 = 61.2$$

$$q_z = 7.5 + 69.84 + 113.68 + 117.6 + 61.2 = 369.82$$

4.1.3. Calculation of Additional Stress

Assuming the upper load is a strip uniformly distributed load, the settlement beneath the centerline with the maximum settlement is considered as the settlement control point. The additional stress $\sigma_z$caused by the action of the strip uniformly distributed load P at that point is calculated using the following equation.

$$\sigma_z = \frac{p}{\pi}\left\{2\arctan\frac{1}{\frac{2z}{b}} + \frac{4\frac{z}{b}}{\left[4\left(\frac{z}{b}\right)^2 - 1\right]^2 + 16\left(\frac{z}{b}\right)^2}\right\}$$

4.1.4. Verification of Bearing Capacity

The calculation formula for the design value of bearing capacity *f* is as follows:

$$f = f_k + \eta_d \gamma_{average}(z - 0.5)$$

The formula is as follows: f_K - Bearing capacity standard value.

η_d — Bearing capacity correction factor for depth

$\gamma_{均}$ — weighted average unit weight of soil above the base

z — foundation depth

Based on the calculation results, it is evident that the foundation bearing capacity does not meet the requirements and requires reinforcement.

4.1.5. Settlement Calculation

The translation of the provided sentence into English would be: "The soft soil foundation consists of two soil layers, namely, silty clay and sandy rock. The total settlement is composed of the settlement of sandy soils such as sandstone and cohesive soils such as silty clay."

$$S_{total} = S_{\text{Silty clay}} + S_{sandstone}$$

Settlement Calculation for Silty Clay:

Settlement Calculation for Cohesive Soil is relatively complex, which includes the instantaneous settlement S_1 when the load is applied, the primary consolidation settlement S_2 caused by the expulsion of pore water in saturated clay under the action of load, and the secondary consolidation settlement S_3 caused by the mutual adjustment of residual stresses between the soil matrix and bound water after the expulsion of pore water and groundwater. Therefore, the total settlement S is calculated as $S = S_1 + S_2 + S_3$.

Settlement Calculation for Sandstone:

Generally, settlement in sandy soil is primarily attributed to instantaneous settlement S_1. This type of settlement is considered to occur immediately after the complete application of the load. It is assumed that this portion of settlement is already fully completed before the track is laid, implying that there will be no post-construction settlement in the sandy soil.

Settlement Calculation Formula:

$$S = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} \beta_i \frac{\sigma_{zi}}{E_{si}} h_i$$

In the equation: β_i — The function of the Poisson's ratiov_i

$\beta_i = 1 - \frac{2v_i^2}{1-v_i}$

σ_{zi} — The average additional stress of each layer.

E_{si} — The compression modulus of each layer.

h_i — The thickness of each layer.

Calculation of final settlement for each layer:

Table 3. Final settlement of each layer

soil layer identification	soil layer	Poisson's ratio	q_{zi} (kpa)	σ_{zi} (kpa)	layer thickness	E (Mpa)	Poisson's ratio	β_i	settlement of each layer(mm)
1	Silty clay (soft plastic)	0.35	7.5	150	0.5	6	0.35	0.623	7.788
2	Silty clay (pliable)	0.3	69.84	150	3.6	6	0.3	0.743	42.57
3	Silty clay (hard plastic)	0.25	113.68	180	5.8	8	0.25	0.833	108.707
4	sandstone (complete weathering)		117.6	200	4.95	10	0.25	0.833	82.467
5	sandstone(strong weathering)		61.2	200	2.72	10	0.25	0.833	45.315

Based on the table above, the settlement for all soil layers is $S = 286.847\text{mm}$

The calculation result indicates that the post-construction settlement is greater than 15mm, which does not comply with the design requirements specified by the code. Therefore, it is necessary to strengthen the foundation to ensure that the post-construction settlement meets the requirements.

As the cornerstone of track structures, the subgrade must maintain the settlement percentage of the track within the required standard range under train operating conditions. This undoubtedly places higher demands on the subgrade settlement stability for high-speed railways. If the subgrade settlement of a high-speed railway is severe, it not only poses significant hazards to the railway itself but also affects train operations. Therefore, the subgrade of a high-speed railway must provide a smooth and stable track foundation for train operations. Consequently, when a high-speed railway passes through soft soil foundations, the stability of subgrade settlement and prediction of post-construction settlement become crucial design considerations in the design and construction of the high-speed railway subgrade. Considering this issue and based on the site's geological survey, this section of the subgrade is proposed to be reinforced with CFG piles.

4.2. CFG Pile Construction Technology

4.2.1. CFG Pile Design Approach

1.design parameters

According to the widely adopted pile spacing and pile diameter, this design proposes to strengthen the entire foundation using CFG (Cement Fly-ash Gravel) piles. The pile diameter is 0.5m, and the pile length extends to the highly weathered sandstone region with higher bearing capacity, with a length of 11m. The piles will be arranged in a square pattern with a spacing of 1.6m.

The cross-sectional area of the pile is:

$$A_p = \frac{\pi d^2}{4} = \frac{\pi 0.5^2}{4} = 0.1963\text{m}^2$$

The rectangular area on the outside of the pile represents the influenced area of the single-pile reinforcement treatment. The length of each side of the rectangle is $a = 2.1\text{m}$

Therefore, the area of the rectangle is calculated as $A_{rectangle} = 2.1 \times 2.1 = 4.41\text{m}^2$

area replacement ratio $m = \frac{A_p}{A_{rectangle}} = \frac{0.1963}{4.41} = 0.0445$

2.load capacity calculation

It is generally believed that after being reinforced with piles, the bearing capacity f of the reinforced soil is composed of two parts: the characteristic value of the soil bearing capacity f_{soil} between the piles and the characteristic value of the pile's bearing capacity f_p. However, in the foundation treatment of high-speed railways, in order to control settlement, it is necessary to fully transfer the load to the CFG piles and minimize the load on the soil between the piles. Therefore, the bearing capacity of the reinforced soil is determined by the pile's bearing capacity.

The bearing capacity of the reinforced soil is calculated according to the following equation:

$$f_{sp,k} = m\frac{R_k}{A_p} + \beta(1-m)f_k$$

In the equation: $f_{sp,k}$ — standard value of composite ground bearing capacity

f_k—standard value of natural ground bearing capacity

m—floor area ratio

A_p—cross-sectional area of CFG single pile

β—coefficient for the exertion of soil strength between piles, taking $\beta = 0.95$

R_k—Standard bearing capacity value of CFG single pile

Sure, the value of R_k can be calculated using the following formula.

$$R_k = \frac{U_p \sum q_{sik}h_i + q_{pk}A_p}{K}$$

In the equation: U_p—Circumference of the pile

q_{sik} — The standard value of ultimate side friction resistance in the i-th layer.

h_i—The thickness of the i-th layer of soil.

q_{pk}—The standard value of ultimate end bearing resistance.

K—The safety factor, taken as 2.0.

Table 4. Single Pile Bearing Capacity Calculation Table

Layer number	soil layer	status	q_{sik}	h_i	q_{pk}	A_p
1	silty clay	ductile	35	0.5	/	0.7854
2		plastic	55	3.6	/	
3		rigid plastic	85	5.8	/	
4	sandstone	complete weathering	220	4.9	5000	
5		intense weathering	170	2.72	/	

Standard value of CFG pile bearing capacity. $R_k = 1442.47\text{kN}$

$$f_{sp,k} = 445kPa$$

$$f > p$$

Based on the calculations, it can be determined that this design satisfies the requirements for bearing capacity calculation. Therefore, the design can proceed.

3.Calculation of compression settlement in the reinforced area of composite foundation.

The settlement of a composite foundation can be divided into two components: the compression settlement in the reinforced area and the compression settlement in the underlying layers. The deformation of the reinforced soil layers in the composite foundation is calculated using the composite modulus, while the deformation of the underlying layers is calculated using the natural ground compression modulus.

Calculation of compression settlement s_1 in the reinforced area.

The composite modulus of a composite foundation is denoted as :

$$E_{sp} = \xi E_s$$

ξ—represents the modulus enhancement coefficient, $\xi = \frac{f}{f_k} = \frac{445}{130} = 3.423$

The compressive strain of the reinforced zone is denoted as S_1

$$S_1 = \sum_{1}^{n} \frac{\sigma_{zi}}{E_{spi}} h_i$$

σ_{zi}—The additional stress increment on the i-th layer of soil

E_{spi}—The composite modulus of the i-th layer of the composite soil

The calculation results are shown in the table below:

Table 5. Calculated results of settlement for each layer

Layer number	layer thickness h_i	compressive modulus E_S	composite modulus E_{sp}	additional stress increment σ_z	reinforced zone compression displacement s
1	0.5	6	20.538	150	3.652
2	3.6	6	20.538	150	26.293
3	5.8	8	27.384	180	38.124
4	4.9	10	34.23	200	28.629
5	2.72	10	34.23	200	15.892

The total settlement of the reinforced area, $S_1 = 112.59mm$

4.2.2. Cushion Layer Installation

The purpose of setting a cushion layer in CFG pile composite foundation is:

1.The distribution of vertical load on piles can be achieved by adjusting the thickness of the cushion layer.

Under normal circumstances, the thinner the cushion layer, the higher the proportion of load borne by the piles. However, if required by the design, the thickness of the cushion layer can be increased.

2.The cushion layer ensures that the piles and soil jointly bear the dynamic loads transmitted from the upper structure. The establishment of the cushion layer is an important requirement for forming a composite foundation with CFG piles.

Setting a cushion layer ensures that the foundation, through the plastic adjustment of the cushion layer, always transfers a portion of the load to the soil between the piles. This ensures that both the piles and the soil between them actively participate in bearing the load. Additionally, the cushion layer can help adjust the horizontal load distribution between the piles and the soil.

3.Setting a cushion layer can reduce the concentrated stress on the foundation base.

When a cushion layer is not used, there is a significant concentration of stress on the piles in the foundation. This concentration of stress should be taken into account in the foundation design, considering the potential damage to the foundation caused by the piles. As the thickness of the cushion layer increases, this stress concentration phenomenon becomes less pronounced. When the thickness of the cushion layer reaches a certain level, the distribution of the reaction forces in the foundation becomes similar to that of a natural foundation.

Based on the aforementioned effects and calculation results, according to the design specifications, it is proposed to use a cushion layer with a thickness of 15cm for this design.

4.2.3. Summary of CFG Pile Design

Based on the aforementioned calculations, the final foundation reinforcement plan can be summarized as follows: To reinforce the soft soil foundation, CFG piles will be used. The CFG piles will have a diameter of 0.5m and a length of 8.9-12.3m, extending to a depth below the highly weathered sandstone layer of 0.5m. The piles will be arranged in a square pattern with a spacing of 1.6m.

A C25 concrete enlarged pile cap will be placed on top of the piles, and a 15cm thick cushion layer will be provided. A layer of biaxial geogrid will be placed on the cushion layer, with a minimum overlap of 2.0m on each side and a tensile strength of at least 130kN/m.

In the section from DK30+000 to DK30+252.73, the bearing capacity of the single piles and the composite foundation is calculated to be 1442.47kN and 445kPa, respectively.In the section from DK30+92.73 to DK30+200.46, where there is an abandoned water pond, appropriate measures such as drainage, dredging, and back filling with compacted soil should be carried out before proceeding with the CFG pile construction.

Please note that this translation is based on the assumption that DK30+000 and DK30+252.73 refer to specific locations or markers on a construction site or project.

The translation of the provided text into English is as follows:

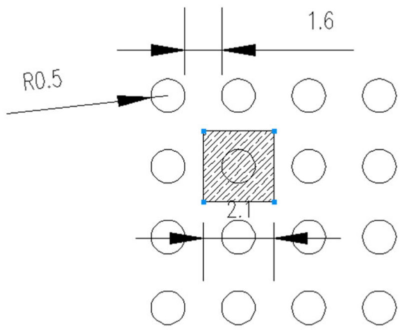

Figure 1. CFG pile layout diagram

5. Summary

The treatment of soft soil foundations should never be oversimplified or based solely on experience. Taking into account various aspects of construction and cost, the installation of CFG piles is the most suitable solution for reinforcing soft soil foundations in high-speed railways.

Development of high-speed railways offers numerous advantages, such as occupying less land area, operating at high speeds, saving time, and causing minimal environmental pollution. High-speed railways have transformed people's perception of time and facilitated communication and transportation between different regions. In the future, high-speed railways in China and around the world will continue to develop to even greater levels. High-speed railways will leave a significant mark on human history.

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